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The Validity of The VmaxPro during Countermovement Jump and Back Squat Performance

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THE VALIDITY OF THE VMAXPRO DURING THE COUNTERMOVEMENT JUMP AND BACK SQUAT PERFORMANCE

by

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ABSTRACT

Background: Advances in technology have resulted in an increase in the utilization of velocity-based training in the strength and conditioning field while utilization of inertia measurement units (IMUs) shows promise. **Methods:** Recreationally trained participants (N=25, 28.3 ± 2.9 years) were recruited to determine the validity of the VmaxPro device for measuring performance variables in the back squat and countermovement jump (CMJ) against a gold standard force plate. Squat variables assessed included mean concentric velocity (MCV), mean concentric power (MCP), depth, and duration while CMJ variables assessed included MCV, MCP, depth, duration, and jump height. Squat variables were assessed across 3 conditions: BW, 50% BW, and 100% BW. **Results:** MCV demonstrated strong correlations in the BW, 50% and 100% conditions (r= 0.965; r=.907; r= 0.827, $p<0.001$). MCP demonstrated strong correlations across all 3 squat conditions (r= 0.979, 0.960, and 0.887, respectively). MCV and jump height demonstrated strong correlation (r= 0.6-0.79) in the countermovement jump (r=0.728 $p<0.001$ and r=0.796 $p<0.001$, respectively). Bland-Altman analysis demonstrated that all measurements fell within the 95% confidence interval between devices. Mean differences between measures showed a consistent overestimation produced by the VmaxPro device. **Conclusion:** The VmaxPro is a reasonably valid device for assessing duration and jump height when assessing CMJ performance as compared to the force plate while demonstrating overestimation bias. For back squat performance variables, the VmaxPro proves as a reasonably valid device for assessing MCV, MCP, depth, and duration while demonstrating overestimation bias in MCV and MCP.

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DEDICATION

I would like to dedicate this thesis to my wife, Vanessa, and my family for their support and patience throughout this process. I also want to acknowledge my best friend and dog, Sully for keeping me company during the writing process and insisting to take mental breaks in the form of long walks. I'm extremely thankful for your support and encouragement as you help propel me to completing this task and furthering my academic career. I am forever grateful and appreciative of your contributions.

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LIST OF ABBREVIATIONS

BPT	Bench Press Throw
CI	Confidence Interval
CMJ	Countermovement Jump
CV	Coefficient of Variation
EMV	Eccentric Mean Velocity
EPV	Eccentric Peak Velocity
ES	Effect Size
GPS	Global Positioning System
HR	Heart Rate
ICC	Intraclass Correlation Coefficient
IMTP	Isometric Mid-Thigh Pull
IMU	Inertia Measurement Unit
KPI	Key Performance Indicators
LPT	Linear Position Transducer
MCF	Mean Concentric Force
MCP	Mean Concentric Power
MCV	Mean Concentric Velocity
MP	Mean Power
MPV	Mean Propulsive Velocity
PBT	Percentage-Based Training
PCF	Peak Concentric Force

PCV	Peak Concentric Velocity
PP	Peak Power
PV	Peak Velocity
RIR	Repetitions in Reserve
RPE	Rate of Perceived Exertion
RSR	Relative Strength Ratio
SD	Standard Deviation
SEM	Standard Error of Mean
SJ	Squat Jump
SmO_2	Local Oxygen Saturation
THb	Total Hemoglobin
TMA	Time Motion Analysis
TRIMP	Training Impulse
VBT	Velocity-Based Training
vGRF	Vertical Ground Reaction Force
VL	Velocity Loss
V_{max}	Maximum Velocity
V_{1RM}	Velocity of 1RM
1RM	One Repetition Maximum
%1RM	Relative training load (percentage of 1RM)

CHAPTER I - INTRODUCTION

1.1 Background

The implementation of technology in sport has allowed sport coaches and support staff to design and monitor training programs in a more scientific manner. Sport coaches measure training load to help prevent injury and overtraining as well as utilizing it as a tool for monitoring performance and adaptation to training (Taylor et. al., 2012). With adequate monitoring of training load, the sport coach can ensure adequate training stimulus, fatigue management, and recovery leading to adaptations that enhance performance. Monitoring training load enhances the clarity and confidence in identifying possible reasons for changes in performance by examining load-performance relationships (Halson, 2014). Providing a sports coach with the capability of examining load-performance relationships can help increase the ability to appropriately prescribe training loads, improve competition preparation, and establish quantitative criteria to assist in return-to-play protocols in the case of injury (Halson, 2014 & Heishman et. al., 2019). Training load is tracked as either external or internal load. External load tracks the mechanical or locomotive work completed by the athlete while internal load tracks the stress placed on the athlete from a physiological and psychological standpoint (Heishman et. al., 2019).

Monitoring internal load can be utilized for identifying fatigue in athletes as well as monitoring and prescribing intensities (Pyne & Martin, 2011). Popular methods used for monitoring internal load include perception of effort (RPE), heart rate (HR), HR to

RPE ratio, training impulse (TRIMP), lactate concentrations, lactate to RPE ratio, HR recovery, HR variability, sleep quality and quantity (Halson, 2014).

While monitoring internal load provides insight to physiological and psychological stress imposed by training and competition, external load monitoring has traditionally been the foundation of most monitoring systems (Halson, 2014). Tracking external load provides sports coaches with quantifiable data that contributes to greater insight of an athlete's work capacity and capabilities. Popular external load measures utilized in sport include power output, speed, accelerations, time-motion analysis (TMA), and neuromuscular function. Time-motion analysis utilizes global positioning system (GPS) tracking or movement pattern analysis via digital video to assess distance and duration of time spent in specified velocity zones. 3D accelerometers or inertial measurement units (IMUs) may also be included to better address accelerations, decelerations, and change of direction measure to create a more comprehensive total load value. Neuromuscular function assessments include testing measurements such as mean power, peak velocity, peak force, jump height, flight time, contact time, and rate of force development (Halson, 2014).

Assessing neuromuscular function periodically throughout the yearly training cycle is utilized by high performance programs to help aid in training decisions to ensure adequate stimulus is provided to enhance athletic performance (Taylor et. al., 2012). Resistance training is an integral part of any athletic training program and due to the various sources of fatigue inducing stressors and individual variability in training response, strength and conditioning practitioners are often required to make individual adjustments to prescribed loading to adhere to changes in neuromuscular function

(Thorpe et. al., 2017). Testing neuromuscular function is often performed on a force platform utilizing jump testing (countermovement/squat jump) and/or isometric mid-thigh pulls (IMTP) (Taylor et. al., 2012; Twist et. al., 2013). However, the practicality of using a force platform can present a challenge due to cost, transportation, scheduling, and time considerations. Recent advances in technology have led the way for the development of devices that are more cost efficient and practical for obtaining testing data as well as intra-training session data. The recent emergence of linear position transducers (LPTs) has provided a more transportable option for testing neuromuscular function via CMJ/SJ tests however, cost limitations may still be of concern for strength and conditioning programs (O'Donnell et. al., 2017). A recent boom in the use of inertial measurement units (IMU) in the strength and conditioning field has created a potentially more cost friendly and space efficient option as compared to the LPT. With the popularity of utilizing the CMJ and SJ for testing neuromuscular function, the ability to use an IMU would provide greater access to testing in absence of a force plate. However, the validity and reliability of using an IMU for such testing is lacking as few studies have tested either jump test with an IMU. Bampouras et. al. (2013) found an IMU to be valid and reliable for assessing force in squat jump tests when compared against a force plate but could not be used interchangeably as the IMU overestimated force. However, McMaster et. al. (2013) found the same IMU unit to lack validity and reliability when testing peak power and peak velocity.

In addition to being used as a potential device for neuromuscular function testing, IMUs allow for the application of velocity-based training (VBT) when performing resistance exercise. Traditionally, periodized training loads are prescribed as a percentage of the athlete's previously established 1 repetition maximum (1RM), which has demonstrated to be effective for creating improvements in strength and power (Rhea & Alderman, 2004). For the strength and conditioning practitioner, the use of percentage-based training possesses inherent problems as maximal strength can fluctuate daily due to arousal state, fatigue levels, sleep quality, and significant increases from continuous training (Knowles et. al., 2018; Perkins et. al., 2001). Due to the aforementioned advances in technology, there has been an increase in the utilization of VBT in the strength and conditioning field. VBT is an alternative method to prescribing loads and assessing athlete performance in training sessions by integrating the use of technology to assess the barbell velocity of an exercise. The benefit of monitoring barbell velocity inter-session helps to guide the training as it can provide instantaneous feedback relating to fatigue by monitoring acute velocity loss. Additionally, it may be used to target specific motor qualities through targeting velocity zones specific to the desired adaptation (Sanchez-Medina & Gonzalez-Badillo, 2011). Velocity-based training works based on the load-velocity relationship, where there is an inverse relationship between relative load and mean concentric velocity, provided the athlete puts forth maximal effort during the concentric portion of the lift (Dorrell et. al., 2020). The load-velocity relationship demonstrates that movements achieve higher velocities at lighter loads and lower velocities at heavier loads. With this, individual load-velocity profiles are established for a given athlete and velocity-based training is then utilized by prescribing loads at a given mean concentric velocity that is individual to the athlete (Gonzalez-Badillo & Sanchez-Medina, 2010). In addition to tailoring the athlete with more individualized prescription of training loads, VBT has shown to enhance motivation, competitiveness, and mood through instantaneous feedback during training sessions (Argus et. al., 2011; Wilson et. al., 2017; Weakley et. al., 2018 & 2019a). VBT has also shown to create greater improvements in strength and CMJ performance as compared to traditional percentage-based training (Dorrell et. al., 2020). Additionally greater movement velocity has demonstrated superior neuromuscular adaptation and greater increases in strength as compared to training that does not prioritize maximal concentric velocity (Gonzalez-Badillo et. al., 2014; Pareja-Blanco et. al., 2014). One use of VBT involves the implementation of velocity loss thresholds where the athlete performs repetitions until the movement velocity drops below a pre-determined cutoff value. Velocity loss thresholds are utilized to prioritize movement velocity and ensure that movement is maintained for the duration of the set. Research has shown that utilizing lower end velocity loss thresholds of 10-20% velocity loss as compared to 20-40% velocity loss yields greater improvement in 1RM strength and CMJ height (Pareja-Blanco et. al., 2016). Additionally, velocity loss thresholds of 10% velocity loss have shown to create greater improvement in velocity and power metrics as compared to 20 and 30% velocity loss thresholds (Weakley et. al., 2019b). With the various avenues in which VBT technology can improve quality of training, the purpose of this study was to assess the validity of a novel field based VBT device against a laboratory gold standard force plate.

1.2 Specific Aims

This research will address the following aims:

1. To measure the validity of the output measures of the VmaxPro IMU device during the back squat across various loads.
2. To measure the validity of the output measures of the VmaxPro IMU device during the countermovement jump.

1.3 Hypothesis

1. The MCV value produced by the IMU will be significantly different than the MCV value produced by the Force plate during the CMJ.
2. The MCP value produced by the IMU will be significantly different than the MCP value produced by the Force plate during the CMJ.
3. The displacement (depth / jump height) value produced by the IMU will be significantly different than the displacement (depth / jump height) value produced by the Force plate during the CMJ.
4. The duration value produced by the IMU will be significantly different than the duration value produced by the Force plate during the CMJ.
5. The MCV value produced by the IMU will be significantly different than the MCV value produced by the Force plate during the body weight squat condition.

6. The MCP value produced by the IMU will be significantly different than the MCP value produced by the Force plate during the body weight squat condition.
7. The displacement (depth) value produced by the IMU will be significantly different than the displacement (depth) value produced by the Force plate during the body weight squat condition.
8. The duration value produced by the IMU will be significantly different than the duration value produced by the Force plate during the body weight squat condition.
9. The MCV value produced by the IMU will be significantly different than the MCV value produced by the Force plate during the 50% body weight squat condition.
10. The MCP value produced by the IMU will be significantly different than the MCP value produced by the Force plate during the 50% body weight squat condition.
11. The displacement (depth) value produced by the IMU will be significantly different than the displacement (depth) value produced by the Force plate during the 50% body weight squat condition.
12. The duration value produced by the IMU will be significantly different than the duration value produced by the Force plate during the 50% body weight squat condition.

13. The MCV value produced by the IMU will be significantly different than the MCV value produced by the Force plate during the 100% body weight squat condition.
14. The MCP value produced by the IMU will be significantly different than the MCP value produced by the Force plate during the 100% body weight squat condition.
15. The displacement (depth) value produced by the IMU will be significantly different than the displacement (depth) value produced by the Force plate during the 100% body weight squat condition.
16. The duration value produced by the IMU will be significantly different than the duration value produced by the Force plate during the 100% body weight squat condition.

1.4 Problem Statement and Purpose of Study

The growing body of evidence surrounding VBT as an alternative to traditional percentage-based programing has created a demand in the market for technology that can accurately assess movement velocity (Abbott et. al., 2020). While gold standards such as 3D motion capture and force plates exist, they are limited to the laboratory setting, making the application of VBT a challenge for strength and conditioning practitioners. The recent growth in companies producing IMUs has allowed for more accessible and cost-efficient application of VBT, however the validity and reliability of IMUs when compared to gold standards have shown to be inconsistent (Abbott et al., 2020; Banyard et. al., 2017; Lake et. al., 2018). In addition to the questions surrounding the validity of IMUs for VBT, most units have been validated against LPTs which potentially introduces additional error that impacts the accuracy assessment of the device (Weakley et. al., 2021). Most studies validating LPTs and IMUs in the back squat have also been performed using a smith machine which removes the element of horizontal displacement bringing in to question their ability to accurately assess a free weight back squat. To date, there are only 3 independent studies that assesses the validity of the novel VmaxPro IMU (Blaumann & Meyer-Sports Technology UG, Magdeburg, Germany) which validated the device against LPTs and 3D motion capture (Fritschi et. al., 2021; Held et. al., 2021; Menrad & Edelmann-Nusser, 2021). While very few studies have looked at validating IMU devices as a viable option for CMJ testing, the introduction of a highly portable IMU unit to accurately assess CMJ performance would be significant for the strength and conditioning field. Therefore, the purpose of this investigation was to determine the validity of the VmaxPro to assesses multiple performance variables of interest to strength and conditioning practitioners against a gold standard. Also of interest, was to determine if the VmaxPro offers a potential alternative to the force plate for analyzing CMJ performance.

CHAPTER II - REVIEW OF THE LITERATURE

2.1 Technology in Sport

2.1.1 GPS Tracking

The integration of technology in sport has steadily grown as technology has advanced and become more accessible to sport coaches and sport support staff members. The utilization of technology in sport has created avenues for obtaining quantifiable data in-game and through training sessions that previously were impossible to measure outside of a lab setting. Global positioning system (GPS) monitoring and inertial sensors have been used in many field sports to help quantify movement demands of sport such as distance, running velocities, change of direction, and accelerations. The data collected from in-game GPS and inertial sensor tracking has been used to monitor training load, helping to create more effective training prescription to help mitigate injury risk (Theodoropoulos et. al., 2020). Catapult Sports, a popular inertial monitor used in field sports, utilizes a combination of accelerometer readings to provide a measure of displacement. Catapult Sports provides a measure known as Player Load™ (PL) that utilizes arbitrary units that are derived from summing the squares of each accelerometer reading and dividing the square root of the value by 100 (Theodoropoulos, et. al., 2020). PL has been shown to be a valuable metric for training prescription considerations. Matching the demands seen in game such as rest period length, time spent in specific velocity zones, and activity duration help recreate game like stimulus during training to foster advantageous physiological adaptation. Catapult Sports' PL metric has been shown to possess greater intra- and inter-player stability as compared to using low speed velocity, high speed velocity, or total distance (Theodoropoulos et. al., 2020). The utilization of these metrics has proven helpful to track acute: chronic load ratios to reduce injury risk associated with overtraining.

2.1.2 IMU Use in Sport

A particularly promising form of technology that has emerged in the sport of baseball is MotusBaseball™ motion capture arm sleeve which places an inertial measurement unit (IMU) right below the medial epicondyle of the elbow. The MotusBaseball arm sleeve helps to quantify elbow torque during the throwing motion in real time through a software app. In addition to elbow torque, other MotusBaseball metrics are provided to measure variables such as arm speed, arm slot, shoulder rotation, and arm stress. Makhni et. al., (2017) utilized the MotusBaseball arm sleeve to compare elbow torque differences amongst different pitch types. Another study compared the MotusBaseball sensor to the OptiTrack biomarker-based motion system to seek validation of the IMU's use for measuring specific kinematic and kinetic variables which included arm speed, arm slot, shoulder rotation and stress (Boddy, et. al., 2019). Magnitude differences between the two systems prevented the MotusBaseball sensor from being validated, however the IMU system was found to be reliable when measuring arm slot, shoulder rotation, and stress.

2.1.3 Blood Lactate Tracking & Near-Infrared Spectroscopy

Blood lactate tracking has been utilized in sport to track an individual's physiological responses to the training workload in real time. With the development of high-quality portable lactate analyzers, practitioners have been able to transport testing that once was confined to the laboratory setting and bring it to the field. By testing athletes blood lactate concentration levels, practitioners can develop individualized lactate profiles showing the athlete's physiological responses to a specified workload. With incremental tests in blood lactate concentration during training, practitioners can monitor training intensity to tailor to the physiological adaptations they wish to address such as aerobic capacity or recoverability from intense bouts of exercise. A study amongst male swimmers at the University of Virginia utilized blood lactate profiling to establish the highest swimming velocity at which lactate threshold was reached. Following the blood lactate profiling, optimal swim velocity for active recovery was tested to promote optimal lactate clearance between 200-m swim trials (Greenwood et. al., 2007).

Sports technology companies have tried to create non-invasive alternatives that measure local oxygen saturation (SmO_2) and total hemoglobin (THb) utilizing near-infrared spectroscopy. One such company is Moxy, which is a muscle oxygen monitor that is placed cutaneously over the targeted muscle. With novel technology, it is important to test their validity and reliability against the gold standards so practitioners can responsibly utilize the technology during field-based training. A group of researchers tested the Moxy oxygen monitor during incremental cycling exercise and found the Moxy to produce reliable SmO_2 measures at low-to moderate-intensity with decreased reliability at high-intensity bouts of cycling (Crum et. al., 2017).

2.1.4 VBT in Strength & Conditioning

In the strength and conditioning field, a recent surge in the use of VBT has occurred as technological advances have provided practitioners with more accessible and affordable options that no longer limit VBT to the laboratory. Prior to the introduction of linear position transducers (LPT), inertial measurement units (IMU), and 3D camera systems, VBT was limited to laboratory settings that utilized force platforms or biomarker-based time motion analysis (Abbott et. al., 2020).

2.2 VBT as an Alternate to Percentage-Based Training

VBT proves as a useful tool for optimizing training of athletes due to the established relationship between load and velocity. A 2006 study examined the effects of various loads on barbell velocity when performing a single set of repetitions to failure in the bench press and half squat exercises (Izquierdo et. al., 2006). The participants of the study included thirty-six physically active males who were all members of the Spanish national Basque ball team (age: 24 ± 2.9 years). In a span of 10 days, participants completed 5 testing sessions with the first session consisting of establishing a 1-repetition maximum (1RM) in both the bench press and half squat. After establishing 1RMs in both exercises, participants came in for an additional 4 sessions where they completed one set of repetitions to failure in the bench and half squat at one of the following submaximal loads (60%, 65%, 70%, and 75% of 1RM). The assigned load for the session were randomized and participants were instructed to perform each repetition with maximal intended velocity during the concentric phase. The mean concentric velocity (MVC) of each repetition was recorded by a rotary encoder (Computer Optical Products Inc, California, USA) which was attached to the end of bar. The key findings in this study demonstrated that for a given exercise, the rate of decline seen in mean concentric velocity (MCV) during each repetition and the number of repetitions performed was the same across different relative loads. The bench press was found to experience greater rates of decline in MCV as compared to the half squat. Results showed that the MCV of the final repetition was similar (no significant difference) at 75% 1RM (0.17 ± 0.04 m/s), 70% 1RM (0.18 ± 0.05 m/s), 65% 1RM (0.18 ± 0.05 m/s), and 60% 1RM (0.17 ± 0.06 m/s) as compared to 1RM (0.15 ± 0.03 m/s) in the bench press exercise. The same trend was found in the squat with the MCV of the final repetition performed at these given relative intensities matching that of the 1RM [75% 1RM (0.31 ± 0.05 m/s), 70% 1RM (0.32 ± 0.07 m/s), 65% 1RM (0.31 ± 0.06 m/s), 60% 1RM (0.33 ± 0.07 m/s), and 1RM (0.27 ±0.02 m/s). These finding demonstrate that when performing repetitions to failure with relative loads ranging from 60-75% 1RM, the final repetition possesses similar MCV as that of a 1RM (Izquierdo et. al., 2006).

Gonzalez-Badillo & Sanchez Medina looked to examine the utilization of movement velocity as an indicator of relative load in the bench press in a 2010 study. Using a LPT to measure mean propulsive velocity (MPV), one hundred and twenty young healthy males (age: 24.3 ± 5.2 years) with at least 1.5 years previous weight training experience performed an isoinertial strength test for the bench press exercise on a smith-machine. During the isoinertial strength test a load-velocity relationship was established through tracking MPV while increasing loads up to a 1RM. A subset of the total sample, consisting of 56 participants returned to perform the same test following a 6 weeks of resistance training. No resistance training was prescribed as the subjects were instructed to continue their usual training routine which consisted of 2-3 session per week utilizing free weights for the bench press 3-5 sets of 4-12 repetitions at 60-85% of their established 1RM. However, the subjects were instructed to perform concentric actions at maximal velocity and to not utilize training that involved training to repetition failure. Key findings in this study showed a near perfect relationship (R^2=0.98) between MPV and load (%1RM). Additionally, the attained MPV associated with each %1RM remained stable, only changing 0.00-0.01 m/s despite the re-test group experiencing an average increase in 1RM of 9.3%. The load-velocity relationship also demonstrated stability regardless of individual differences in strength levels. Participants were ranked and split into 4 groups according to their relative strength ratio (RSR). Group 4 consisted of the strongest participants and demonstrated a significantly lower mean test velocity ($P<0.05$) as compared to the other three groups, however there were no significant differences found in 1RM mean propulsive velocity (V_{1RM}) between groups (Gonzalez-Badillo & Sanchez-Medina, 2010). As relative load increased by 5% increments from 30-100% 1RM there was an observed decrease in velocity that varied between 0.07 and 0.09 m/s, indicating that when a participant experiences a difference of 0.07-0.09 m/s at given absolute load there could be a 5% increase/decrease in their bench 1RM value.

In comparison, Conceição and colleagues (2015) further investigated if the load-velocity relationship existed across three lower limb exercises consisting of leg press, full squat, and half squat. Using a cross-sectional study design, 15 national and/or international level male track and field athletes (jumpers and sprinters) with at least two years of resistance training experience went through a familiarization trial 48 hours prior to the start of data collection sessions. During the familiarization trial the athletes performed 5 repetitions of each exercise starting with light loads which consisted of 40 kg for the leg press and 20kg for the full and half squat. Participants attained 90° knee flexion for the half squat and full knee flexion for both the full squat and leg press exercises. Once attaining the desired end range of motion, participants were asked to hold the position for 3-4 seconds before extending the knee at maximal voluntary velocity to eliminate the elastic energy contribution from the muscle tendon unit. To ensure linear movement, exercises were performed on a smith machine and inclined leg press machine while the movement velocity was assessed by a LPT (T-Force System, Ergotech, Murcia, Spain). After the familiarization trial, data collection sessions began which consisted of three sessions targeting one of the three exercises with a minimum of five days rest between sessions. For each exercise a load progression consisting of six to eight load increments were used with a starting weight of 20kg in the half and full squat and 60kg in the leg press. As demonstrated in previous bench press studies, load increments increased by approximately 10% 1RM until a MPV of 0.5 m/s was attained. Once a MPV of 0.5 m/s was reached load increments increased anywhere from 5 to 1kg until a 1RM was established. Four repetitions were performed for loads that established a MPV of 1.15 m/s followed by a 3- to 4-minute rest interval. Loads that were performed at a MPV range of 0.5- 1.15m/s were performed with two repetitions followed by a 5-minute rest interval while maximal loads that were performed at <0.5m/s were performed with one repetition and 6 minutes rest. The findings show there is a strong relationship between maximum velocity (V_{max}) and the %1RM for all exercises: full squat (r^2_{adj}=0.94, P <0.0001), half squat (r^2_{adj}=0.97, P <0.0001), and leg press (r^2_{adj}=0.96, P <0.0001) respectively. Additional findings also demonstrated a strong relationship between MPV and %1RM for all three exercises: full squat (r^2_{adj}=0.95, P <0.0001), half squat (r^2_{adj}=0.96, P <0.0001), and leg press (r^2_{adj}=0.96, P <0.0001). These key findings add to the scientific literature demonstrating the load-velocity relationship can be found across a variety of lower body exercises as well as demonstrating a linear relationship that establishes the use of MPV for 1RM estimations. For every 5% load increase from 30% to 100% of 1RM, the full squat, half squat, and leg press were seen to have a MPV difference of 0.087, 0.06, and 0.066 m/s, respectively (Conceição et. al., 2015). Indicating a potential 5% increase in 1RM when a participant increases their MPV at an absolute load by its exercise associated velocity increment, building on the findings from Gonzalez-Badillo and Sanchez-Medina (2010).

Building on the nearly perfect linear relationship between movement velocity and %1RM, Dorrell and colleagues (2020) looked to compare VBT and percentage-based training (PBT) on increasing maximal strength and power adaptations amongst 16 resistance-trained men. Utilizing a randomized control research design, the research team looked to examine the effects of manipulating load based on MPV within a 6-week training program. Participants had a minimum of 2 years of resistance training experience and had participated in continuous resistance training for at least 6 months prior to training intervention. The 6-week resistance program consisted of two training session per week with a base program existing between the VBT and PBT groups. The training program followed a wave-like periodization structure with number of sets, relative training loads (%1RM), and inter-set rest periods equated between the two groups. To ensure supplementary exercises included in the resistance training were equated, both groups performed the same sets and reps with the load assigned based off body mass or through repetitions in reserve (RIR). The compound movements utilized included back squat, bench press, strict overhead press, and deadlift with these lifts being programmed based on the group designation, VBT or PBT. Proper integration of velocity monitoring on these key exercises for the VBT group included the use of velocity zones and velocity stops. Previously published data and pretesting 1RM assessments were used to establish group velocity zones for each key movement at various relative loads. The velocity stop threshold was set at 20% velocity loss below the targeted velocity zone for the VBT group, creating load increments/decrements based on the participant's current performance as compared to the established group load velocity profile (LVP). Pre- and post-testing included performing a CMJ utilizing a Just Jump mat (Probiotics, Huntsville, AL), a 1RM test for bench press, strict overhead press, deadlift, and back squat with each of these being analyzed with a LPT (GymAware PowerTool; Kinetic Performance Technology, Canberra, Australia) to establish group MPV zones at relative loads. Pre-testing showed no significant differences in any analyzed variables between the VBT and PBT prior to the 6-week training intervention. Post-testing revealed significant increases in maximal strength for both groups in bench press (VBT 8%, PBT 4%), strict overhead press (VBT 6%, PBT 6%), and back squat (VBT 9%, PBT 8%) with only the VBT group experiencing significant increases in the deadlift (VBT, 6%) respectively (Dorrell et. al., 2020). A significant group by time effect ($F_{(1.14)} = 11.50$, $P = 0.004$) indicated a significantly greater increase in bench press 1RM for the VBT group when compared to the PBT group. Additionally, the velocity stops created significantly less training volume for the VBT group in the bench press (6%), strict overhead press (6%), and the back squat (9%) in comparison to the PBT group. Additionally post-testing revealed a significant group by time effect ($F_{(1.14)} = 7.14$, $P = 0.018$) between the VBT and PBT training groups for CMJ. The VBT group experienced significant increases in CMJ performance as compared to the PBT group (5% vs. 1% respectively). These findings support that VBT may elicit favorable adaptations in vertical jump and maximal strength as compared to the traditional PBT loading despite significant reductions in training volume. These findings are compelling for the strength and conditioning practitioner as utilizing MPV can allow for greater fatigue monitoring and training load prescription without the need to perform the traditional RM testing protocols (Dorrell et. al., 2020).

2.3 Velocity as Feedback for Performance Enhancement

The utilization of VBT in the strength and conditioning field also provides enhanced performance through multiple forms of feedback. A study by Argus and colleagues (2011) explored the acute effects of verbal feedback on explosive upper-body performance in the bench throw exercise amongst elite male rugby athletes. The study participants consisted of 9 elite rugby union athletes from Super 14 professional rugby teams and assessed their bench-throw exercise during the competitive phase of their season. The participants performed a standardized warm up prior to completing 3 sets of 4 reps of bench-throws on a Smith machine utilizing a load of 40 kg. Participants performed 4 separate training sessions with 7 days between each session. Each participant completed two sessions with peak velocity (PV) feedback provided on each rep as well as two sessions where no feedback was provided each rep. Hand positioning and depth during the eccentric loading phase were self-selected by the participants before attempting to propel the bar for maximal velocity. A two-minute rest was utilized between sets with each athlete being prompted to rate their effort after each set (Argus et. al., 2011). Average peak power of all repetitions experienced a small increase of 1.8% when verbal feedback was administered. No average peak power difference was found between the first set of each condition. In the second and third sets the feedback condition demonstrated a small increase in average peak power (2.4% and 3.1% respectively). When feedback was provided, average PV of all repetitions improved by 1.3%, representing a small effect. When comparing each set, feedback provided an increase in average PV across all sets. (1.3% for set 1, 1.1% for set 2, 1.1% for set 3).

Building on the potential benefits of verbal feedback resulting from instantaneous kinematic metrics provided by VBT devices, Weakley et. al. (2018) evaluated the effects of visual kinematic feedback, verbal kinematic feedback, and verbal encouragement on resistance training performance. Participants included 12 male semiprofessional rugby union players with at least 2 years of resistance training experience participated in the study. All participants had completed an 8-week standardized off-season training program. Prior to completing the four feedback condition testing sessions, participants completed a familiarization and testing session which included a 3RM back squat to establish relative test loading. Each participant came in for 4 separate testing sessions with randomized feedback conditions where they performed a set of 10 reps of back squat with 75% of their 3RM. The four testing conditions were performed with 3-4 days rest between sessions. Each session mean concentric velocity was measured using a LPT (GymAware PowerTool; Kinetic Performance Technology, Canberra, Australia). The verbal kinematic feedback condition consisted of the lead investigator verbally stating the MPV at a volume slightly louder than conversation volume. The visual kinematic feedback condition utilized a mounted iPad which displayed MPV. The verbal encouragement conditions consisted of the lead researcher providing standardized verbal encouragement during reps 2-9. The control condition consisted of completing the test void of any verbal encouragement, verbal feedback, or visual feedback while MPV was recorded. The MPV (mean ± SD) across the entire set of the four conditions were similar: verbal encouragement [0.64 ± 0.04], verbal [0.64 ±0.03] and visual kinematic feedback [0.64 ± 0.04], and control [0.61 ± 0.04]. When feedback or encouragement was supplied to the athlete there were moderate improvements in MPV as compared to the control group. Average MPV was *almost certainly* greater (ES ± 90% CI) across the 10 repetitions when verbal kinematic feedback (0.86 ± 0.21), visual kinematic feedback (0.77 ± 0.19), and verbal encouragement (0.74 ± 0.22) were used for feedback as compared to the control group. There was a small, possible to likely increase in MPV when performing the final repetition when comparing the verbal kinematic condition to the visual kinematic (0.25 ± 0.43) and the verbal encouragement (0.37 ± 0.42) conditions (Weakley et. al., 2018).

Weakley and colleagues (2019) assessed the effects of visual kinematic feedback on MPV during the back squat amongst adolescent athletes as well as the effects of kinematic feedback on motivation, competitiveness, and perceived workload. This study used a randomized crossover design in which 15 sub-elite adolescent rugby athletes performed the back squat on two separate occasions with and without visual kinematic feedback. The two trials were separate by 7 days. Participant's motivation level was assessed before and after exercise via questionnaire. After completing the exercise, the athletes completed a questionnaire regarding their competitiveness levels and overall perceived workload experienced during task completion. All participants had at least 6 months previous experience with the back squat exercise within their resistance training. Participants completed a standardized warm-up followed by one set of 10 reps at 65% of their previously established 3RM. While completing the feedback trial the participants received visual kinematic feedback via iPad which displayed mean concentric barbell velocity following completion of each barbell back squat repetition. All mean concentric barbell velocities were collected using a LPT (GymAware PowerTool; Kinetic Performance Technology, Canberra, Australia). Competitiveness was measure via questionnaire using an adapted version of the 4-item competitiveness scale from Anderson and Carnagey. Subjective task-related workload was gauged via The National Aeronautics and Space Administration Task Load Index which measured mental demand, temporal demand, perceived physical demand, performance, effort, and frustration which were aggregated together to produce a 'global workload' score. Mean concentric barbell velocity for all participants for the feedback condition was 0.70 m/s (±0.04) while the mean concentric barbell velocity for the control condition was 0.65m/s (±0.05). Practical significance using magnitude-based inferences showed there were *almost certainly* (>99.5%) greater mean concentric velocity for the Feedback condition. Individual repetition inferences ranged from *possibly* (25-75%) to *almost certainly* greater.

Inferences for pre- and post-motivation, competitiveness, and perceived workload were all found to be *almost certainly* greater with the Feedback condition. On a 10-pt Likert Scale, the feedback condition reported *almost certainly* greater values for mental demand (7.87 ± 0.92 vs. 6.13 ± 1.30), perceived physical demand (7.13 ± 0.99 vs. 5.40 ± 0.91), temporal demand (7.40 ± 1.45 vs. 6.27 ± 1.16), performance demand (7.47 ± 1.30 vs. 6.07 ± 0.70), and effort (8.07 ± 0.80 vs. 7.33 ± 0.82). In the control condition, frustration was reported to be *almost certainly* greater (1.60 ± 1.12 vs. 4.60 ± 1.18). These findings suggest that it could be highly beneficial to provide male adolescent athletes with visual feedback throughout resistance training sessions to improve the quality of training sessions. It is suggested that improved training quality could result in greater training adaptation. From the results in this study, the mean set velocity improvement of 7.6% as a result of visual kinematic feedback suggests this feedback modality could be worthwhile in the development of adolescent athletes (a. Weakley et. al., 2019). The use of immediate feedback may show to have been responsible for improvements in motivation and competitiveness which ultimately created performance improvements during exercise. Immediate feedback could have a potential impact on the psychological state creating improvements in physical performance and outcomes.

In comparison to the works of Weakley et. al. (2019), a study produced by Wilson et. al. (2017) assessed the effects of providing real-time quantitative feedback on lifting performance as well as the effects of feedback on subjective measures such as task competitiveness, motivation, mood, and workload. The following study utilized repeated measures with the task order counter balanced. Participants included 15 male sub-elite rugby union athletes that possessed at least 6 months experience with resistance training and the barbell back squat exercise. Prior to testing, the athletes had their 1RM back squat estimated through pre-testing one week prior to participating in the feedback or No-feedback trials. Participants completed the two trials one week apart performing 1 set of 10 repetitions at 60% of their estimated 1RM. MPV was measured during both trials with the feedback trial placing an iPad at eye level displaying the MPV to the participant following each repetition. In the no feedback condition participants were not shown these values. During both conditions no other verbal feedback and communication was provided throughout the entirety of the task. Following completion of the task participants completed a NASA-Task Load Index to measure subjective workload as well as a competitiveness questionnaire, post-task questionnaire which measured motivation and mood. A significant main effect for condition ($p = .005$) was observed between the feedback condition and the no-feedback condition with the feedback condition (M= 0.65 m/s ± 0.05) yielding significantly greater MCV while performing reps as compared to the no-feedback condition (M = 0.70 m/s ± 0.04). The feedback condition possessed significantly greater task competitiveness ($p < .001$). Motivation increased pre-task to post-task in the feedback condition while a reduction was observed for the no-feedback group, with significant differences seen in the change scores ($p = .002$). These findings show potential benefit in providing real-time objective performance feedback to improve motivation and mood, which may point to integrating instantaneous visual feedback through technology as a means to promote engagement and exercise adherence (Wilson et. al., 2017).

2.4 Phases of The CMJ and Processing CMJ Data

The use of the CMJ in strength and conditioning has become common practice for identifying performance changes and neuromuscular fatigue in athletes. The utilization of a force plate to collect CMJ data is recognized as the gold standard, however the raw data must be properly processed and analyzed in order to accurately assess the CMJ. A paper by Chavda and colleagues (2018) was published with the intent of helping strength and conditioning practitioners better understand the force-time curve, adequately identify the key phases of the CMJ, the process of deriving the variables from their corresponding phases, and how to set up an excel macro to process the raw data. The countermovement jump consists of six phases: (1) weighing phase, (2) unweighting phase, (3) braking phase, (4) propulsion phase, (5) flight phase, and (6) landing phase. Prior to collection, the force plate is zeroed before instructing the participant to step onto the force plate. At this point the weighing phase takes place when the participant is standing in a ready postion while remaining motionless for at least one second (Chavda et. al., 2018). At this point in the time the participant's bodyweight is collected by averaging the motionless period. The excel sheet can be set up to convert the bodyweight (N) into mass (kg) by dividing the bodyweight (N) value by the force of gravity (9.81). The start of the jump is identified as the first time-domain signal that is less than 5 standard deviations of the particpant's previously averaged bodyweight (N) value, once this signal is obtained, the jump has been initiated resulting in a velocity value less than zero. This indicates the intitiation of the unweighting phase. The end of unweighting phase is identified as the point when the vertical ground reaction force (vGRF) reaches a value equal to the bodyweight (N) of the participant (Chavda et. al., 2018). However, this can also be identifed as the lowest attained velocity which corresponds to the end of the negative acceleration that occurs during the phase. Once the end of unweighing phase has been identified, the breaking phase occurs. The end of the breaking phase represents the point in time when the participant undergoes the amortization phase of the stretch shortening cycle, switching from an eccentric to a concetric motion that leads to propulsion. The braking phase is where the participant decelerates their center of mass. This is identifed by the increase in force past the participant's bodyweight (N) and velocity increases to zero (McMahon et. al., 2018). Following the breaking phase, the propulsion phase begins. The onset of the propulsion phase is identified as the moment positive velocity occurs after zero velocity is achieved during the breaking phase. During the propulsion phase, force output reaches it peak before decreasing down to zero. This reduction in force after peak force has been attained refers to the point at which the athlete's feet have left the floor prior to "flight". At this point the participant's center of mass is higher than the initial weighing phase center of mass and has reached zero acceleration (Chavda et. al., 2018). Peak velocity is attained during the propulsion phase moments before "flight" occurs. The onset of the flight phase is identifed as the take-off point, which is identified in excel by identifying the smallest value that is less than or equal to 10 N (Chavda et. al., 2018). The flight phase is the moment the athlete leaves the force plate with the goal of attaining maximal displacement of their center of mass (jump height). At this point force is zero throughout the duration of the flight phase and velocity is seen to decrease to the point of zero velocity, which signifies the point at which maximal displacement has occurred (Chavda et. al., 2018). From that point forward velocity continues to decrease in the negative direction due to the effects of gravity. The flight phase has ended once touchdown has occurred which transitions ino the landing phase which is identified by a rapid increase in force. The landing phase will experience the peak force of the entire movement with peak landing force identified as the largest spike following touchdown. The landing point is identifed as the first value greater than 10 N between the peak displacement and peak landing force (Chavda et. al., 2018).

Key variables derived from the raw force data include acceleration, velocity, displacement, and power. Chavda and colleagues (2018) outline the equations used to derive the variables. Acceleration is calculated by dividing the net force by the athlete's mass. Once acceleration is calculated, it is then integrated to velocity, by adding the initial velocity to the product of acceleration and time ($V = v_i + at$) (Chavda et. al., 2018). Displacement is obtained by intergrating velocity. This is achieved by taking the difference between intital velocity and final velocity and multiplying it by the time interval between the two velocity values and dividing it by two ($s = \frac{1}{2}\left(v_f - v_i\right)t$). In this case the time duration between the two values will correspond to the time point which will be dependent of the frequency of the instrument (Chavda et. al., 2018). It is important to note the necessity of converting the sampling frequency from hertz (Hz) to time (s) to represent how many data points are collected within a 1 second time frame. The final variable of interest is power, which is solved for by multiplying velocity by force with respect to the associated time stamp ($P = F \: x \: v$).

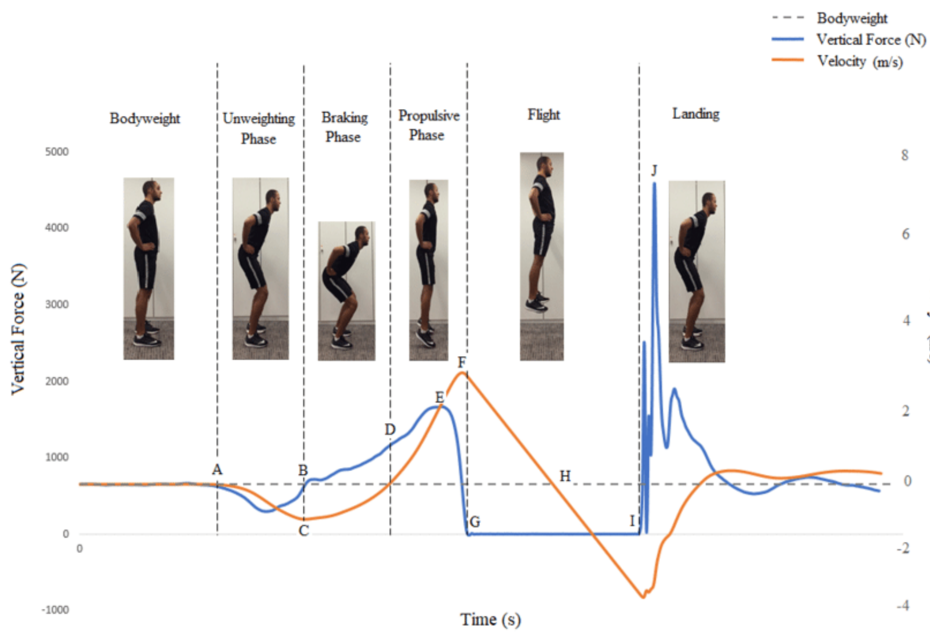

Figure 2.1 *Phases of the CMJ*

Force- and velocity-time record of a countermovement jump broken into the phases of the countermovement jump (Chavda et. al., 2018)

2.5 Kinematic-Kinetic Methods of Processing Squat and Jump Data

Cormie and colleagues (2007) assessed the validation of power measurement techniques when performing various dynamic lower body resistance exercises. The intent of the study was to examine differences between kinematic and kinetic methodologies used in power measurement research while concurrently validating those techniques to the methodology of using two LPT's and a force plate. Study participants consisted of ten division I football and track and field athletes who possessed a minimum of 4 years of previous resistance training experience. Over the period of three testing sessions, each participant performed one of the following exercises in each session: jump squat, back squat, or power clean. A preliminary session was held where 1RM for each exercise was established (Cormie et. al, 2007). The following intensities were used for both the squat and jump squat sessions: 0, 12, 27, 56, 71, and 85% 1RM. For the power clean session intensities of 30, 40, 50, 60, 70, 80, and 90% 1RM were used. Participants were instructed to perform the exercises at maximal effort while performing a minimum of two trials at each loading condition (Cormie et. al., 2007). All data was collected at 1000 Hz on a AMTI force plate with three LPTs attached to both the left and right sides of the barbell. The following six methodologies were used to calculate vertical force, velocity, and power from each trial: 1-LPT, 1-LPT+Mass, 2-LPT, Force plate (FP), 2-LPT+FP, 2-LPT+FP (Cormie et. al., 2007). Peak concentric force (PCF), peak concentric velocity (PCV), peak power (PP), mean concentric force (MCF), mean concentric velocity (MCV), and mean concentric power (MCP) were measured via the six different methodologies. Comparisons of PP outputs at the optimal loads for the three exercises were used to assess the reliability of the six various methods.

The kinematic methods used for calculating kinetic and kinematic variables consisted of the 1-LPT, 1-LPT+Mass, and 2-LPT methodologies. These LPT based methodologies directly measured bar displacement while the LPT while producing a voltage signal that allowed for displacement-time data to be calculated (Cormie et. al., 2007). From the displacement (*d*) and time (*t*) data, instantaneous vertical velocity (*v*) was calculated at each time stamp ($y = \frac{\Delta d}{\Delta t}$). Acceleration of the system (*a*) was calculated by using the change in displacement over the change in time raised to the second power ($a = \frac{\Delta d}{\Delta t^2}$). Force ($F$) was then calculated by adding the acceleration of the system (a) and the acceleration due to gravity (a_g) and multiplying the sum by the total acceleration to the mass of the system (SM = body mass + external load), $F = SM * (a + a_g)$ (Cormie et. al., 2007). Power is then calculated at each time point by multiplying force and velocity ($P = F * v$). In the 2-LPT method, both LPTs for a triangle with barbell allowing for both measures of vertical and horizontal movements to assess vertical displacement. The same calculations are used for assessing velocity, acceleration, force, and power based off of the measured displacement variables. However, the 1-LPT+Mass method varies in that the force is accounted for differently. In this methodology Force is a constant throughout the measured movement due to how it is calculated. In this method Force is equivalent to product of the system mass and acceleration due to gravity ($F = SM * a_g$) (Cormie et. al., 2007). The FP method makes up the only kinetic method of the six used methodologies. Due to the fact that the initial vertical velocity of the system is always zero, the FP method can determine power output from vGRF. vGRF is used to determine acceleration by dividing force by the system mass at each instantaneous time point (i), $a_{(i)} = \frac{F_{(i)}}{SM}$. To guarantee that only the acceleration produced by the subject is used to determine velocity, the acceleration due to gravity is subtracted from all calculated accelerations (Cormie et. al., 2007). The product of acceleration and time data at each time stamp is used to calculate the instantaneous vertical velocity of the system, $v = \Delta a * \Delta t$. Power is then calculated by multiplying the measure force values by the derived velocity data ($P = F * v$). The Kinematic-Kinetic

Methods for determining power output consisted of the 1-LPT +FP and 2-LPT+FP methodologies. In both of these methods, the LPTs determined displacement which was derived to determine velocity values while the FP directly measured the force. From this point power was calculated by multiplying the FP force values by the derived velocity values from the LPT devices (Cormie et. al., 2007).

To determine if significant differences existed between the six methodologies in their measurement of vertical velocity and power, a repeated measures ANOVA was utilized with additional comparisons made to determine their impact on the load-power relationship at different loading conditions (Cormie et. al., 2007). When looking at the jump squat exercise the 1-LPT+Mass methodology produced significantly different ($p \leq 0.05$) PP and MP outputs at the optimal load as determined by the 2-LPT+FP methodology, resulting in underestimations in both variables. The FP methodology produced significantly different ($p \leq 0.05$) MP outputs at the optimal load as determined by the 2-LPT+FP methodology, resulting in underestimation of the value. When performing the squat, the 2-LPT and 1-LPT methodology produced significant differences ($p \leq 0.05$) in PP output at optimal loads as determined by the 2-LPT+FP methodology, resulting in overestimation of the value (Cormie et. al., 2007). The following study highlights the disconnect in measured variables when they are derived or integrated as compared to instruments that perform direct measures of the variable. In addition, this study highlights the power variables change based on the data collection methodology used, demonstrating that 2 of the 3 kinematic data systems elevated power output across various loads in the squat jump and squat while the force plate tended to under-represent velocity and power outputs (Cormie et. al., 2007).

2.6 Reliability and Validity of Various Velocity Variables

2.6.1 Background

A variety of velocity variables are utilized in the field of strength and conditioning as well as research, with the most common variables including mean concentric velocity (MCV) and peak velocity (PV). MCV provides the average velocity across the concentric phase while PV provides the peak instantaneous velocity achieved during the concentric phase (Weakley et. al., 2020). Sanchez-Medina, Perez, and Gonzalez-Badillo have proposed mean propulsive velocity (MPV) as an alternative to MCV when assessing strength and power. MPV helps to remove the braking phase of the concentric muscle action by removing the concentric phase where acceleration drops below -9.81 m/s. Sanchez-Medina and colleagues found that during the bench press exercise the braking phase no longer existed once reaching a relative intensity of 76.1 ± 7.4% 1RM. With these findings it is proposed that utilizing MPV may help avoid underestimating the neuromuscular potential of an individual when lifting at light to moderate loads (Sanchez-Medina et. al., 2009).

2.6.2 Velocity Variables in Upper Body Exercise

Given the wide use of these three velocity variables throughout strength and conditioning, both in the field and research, Garcia-Ramos and colleagues conducted a study utilizing the bench press exercise to determine whether MPV, MCV, or PV was more reliable in determining relative loads (2018). The following study was a repeated measures design conducted amongst 30 college aged males with at least 2 years of resistance exercise training experience. The following two exercises were utilized to compare the linearity, reliability, and accuracy of the three velocity variables, the concentric-only bench press throw and the eccentric-concentric bench press throw (BPT). Both exercises were performed on a smith machine with a LPT (T-Force System; Ergotech, Murcia, Spain) which tracked the three velocity variables. Following two familiarization trials, the participants came in for testing on four occasions, twice a week where they performed one of the two randomly assigned BPT exercises in back-to-back visits with at least 48 hours of rest between sessions. To obtain individual load-velocity relationships in both BPT exercises, participants began testing with an external load consisting of a 17kg bar making 10kg incremental jumps until a MPV lower than 0.5 m/s was achieved. After hitting this MPV threshold, the load was progressively increased in 1-5kg increments until a 1RM was established. For loads that established a MPV greater than 1 m/s, three attempts were performed, loads that possessed a MPV between 0.65-1.0 m/s, two attempts were performed, and a single attempt was performed at each load that established a MPV below 0.65 m/s. For both BPT exercises, the ability to throw the barbell ceased around roughly 75% of 1RM resulting in performing either a concentric-only bench press or eccentric-concentric bench press. When analyzing the individual load-velocity relationships, only the repetitions with the highest velocity value for each relative load was utilized. Regardless of velocity variable, the individual load-velocity relationship possessed a very strong linear relationship in both BPT exercises [(concentric only BPT: r^2 = 0.989 for MV, 0.983 for MPV, 0.974 for PV), (eccentric-concentric BPT: r^2 = 0.993 for MV, 0.980 for MPV, 0.974 for PV)] A two-way repeated measures ANOVA was used which revealed an significant main effect for the velocity variable (P < .001) as well as an significant interaction effect (P < .001). A Bonferroni post-hoc comparison showed that MV displayed the highest strength in regard to the load-velocity relationship followed by MPV and finally PV. A general regression equation to predict estimated relative load (%1RM) based on each velocity variable was produced for both BPT exercises. The accuracy of the general regression equations to predict relative load (%1RM) from movement velocity was highest for MV (SEE= 3.80-4.76% 1RM) followed by MPV (SEE= 4.91-5.56% 1RM) and PV (SEE= 5.36-5.77%). Not only did MV possess the most linear load-velocity relationship, but it also provided the greatest accuracy in predicting relative load (%1RM) from the general regression equation (Garcia-Ramos et. al., 2018).

2.6.3 Velocity Variables in Lower Body Exercise

The load-velocity relationship has been shown exist across multiple exercises, allowing VBT to be used for prescribing loading intensity and estimating 1RM. Sanchez-Medina and colleagues (2017) looked to build on the 2015 findings produced by Conceição and colleagues which demonstrated a very close relationship between relative load and MPV in the leg press, half squat, and full squat exercises. Sanchez-Medina et. al. (2017) consisted of 80 male participants who were senior national level athletes in their sport that had 4-12 years of experience with resistance training. Additional inclusion criteria included having performed 2-4 resistance training sessions per week over the past 12 months which incorporated the squat exercise in their training. Participants underwent two preliminary familiarization sessions where squat depth was assessed using goniometer to ensure a knee angle less than 45 degrees was obtained to constitute a deep squat. In addition, several practice sets were performed with loads between 20-60% 1RM. Testing was conducted over two sessions with the first session being used for medical examination, personal data, body composition assessment and administration of a health history questionnaire. The second testing session consisted of progressive load testing of the high-bar deep back squat exercise to determine 1RM strength and individual load-velocity relationship. The high-bar back squat was performed in a smith-machine with a LPT (T-Force System Version 3.60, Ergotech, Murcia, Spain) which provided visual and auditory velocity feedback following each repetition to encourage maximal intent velocity. To ensure standardization, the eccentric phase of the back squat was performed with a controlled mean bar velocity between 0.50-0.70 m/s. Additionally, to avoid excessive range of motion reduction with increasing loads, eccentric displacement was monitored and limited to a 10% loss in eccentric distance. The testing protocol consisted of 3 attempts at light loads with a MPV greater than 1.15 m/s, 2 attempts at moderate loads with a MPV ranging from 0.70-1.15 m/s, and 1 attempt for the heavy loads which possessed a MPV less than 0.70 m/s. Participants continued to increase by small 2.5-5kg increments until a 1RM was established. Light to moderate loads were given 3 minutes rest between sets with heavy loads given 5 minutes rest between sets. For data analysis, the repetition with the highest MPV was used to determine the individual load-velocity profile with three velocity variables analyzed as performance measures: MV, MPV, and PV. All three velocity variables were analyzed and plotted against %1RM with loads less than 40% 1RM eliminated due to the inability to maximally apply force into the ground without turning the squat into a jump. With load this light, there is a larger breaking phase during the concentric portion of the lift which limits the ability to produce maximal velocity. From the data analysis, a very close relationship was established for MV (R^2 = 0.955) and MPV (R^2 = 0.958) while PV (R^2 = 0.794) demonstrated a lower association. To determine if strength levels changed load-velocity relationship, participants were ranked according to their RSR and divided into 3 subgroups: G1, n=24, RSR, ≤ 1.30; G2, n=29, 1.30< RSR ≤ 1.50; G3, n=27, RSR > 1.50 (Sanchez-Medina et. al., 2017). However, strength levels possessed no significant effect on the load-velocity relationship as no significant difference was found for the MPV attained at each %1RM or the velocity of the individuals 1RM (V_{1RM}). There was no correlation between RSR and V_{1RM}. The %1RM prediction equations derived from the 3 velocity variables were most reliable when using MPV (R^2 = 0.954; SEE = 4.02%) and MV (R^2 = 0.948; SEE=4.31%) with PV (R^2 = 0.954; SEE = 8.57%) being the least reliable of the three values.

2.7 Velocity Loss Thresholds for Performance Enhancement and Fatigue Management

Greater movement velocity has been shown to yield superior neuromuscular adaptation and improved training effect such as greater increases in strength as compared to training where maximal velocity is not prioritized (Gonzalez-Badillo et. al., 2014 & Pareja-Blanco et. al., 2014). With those findings, the use of velocity loss thresholds for fatigue management have become a common practice amongst VBT strength practitioners. Velocity loss thresholds are used as cutoff points for a working set when

MVC drops below a certain velocity. A 2019 study by Weakley and colleagues looked to examine the individual variability in the number of repetitions that can be completed within various velocity loss (VL) thresholds. The team of researchers utilized VL thresholds of 10%, 20%, and 30% to examine kinetic and kinematic changes as well as repetition characteristics in the free-weight back squat exercise. Utilizing a counterbalanced crossover design, 16 male team sport athletes with at least two years of previous resistance training experience participated in the study. All participants had been completing the back squat exercise for the past three months with a frequency of at least two times a week utilizing intensities between 60-93% 1RM. Following a familiarization trial, participants completed three testing trials separated by at least 72 hours with each trial utilizing one of the three VL thresholds. Each testing trial, the participant performed a squat specific warm-up, working up to a load that produced a MCV of .70 ±0.01 m/s which establish the individuals working set load that was utilized for their following sets of back squats. One of the three VL threshold conditions was applied which decided when to terminate the exercise set. Set termination was set at the following MCV for their respective conditions; 0.63 m/s for the 10% protocol, 0.56 m/s for the 20% protocol, and 0.49 m/s for the 30% protocol. Participants performed 5 working sets with three minutes of recovery. Loads were adjusted in sets 2-5 to maintain the goal MCV of 0.70 m/s if the first repetition of the set was not within the normal variation of ±0.06 m/s that was previously established in the research teams pilot study. Velocity data was collected via LPT (GymAware, Kinetic Performance Technology, Canberra, Australia) and mean and peak concentric kinematic and kinetic outputs averaged for all five sets across each VL threshold protocol and then further analyzed using linear mixed effect models with a 90%

confidence interval (CI). When compared to the 10% VL threshold protocol, MCV and PV of each set was likely to most likely lower during the 20% and 30% VL threshold protocols. When compared to the 10% VL threshold protocol, mean power (MP) and peak power (PP) of each set was very to most likely lower during the 20% and 30% VL threshold protocols. When comparing repetitions performed, the 30% VL threshold protocol saw participants ‘very likely’ perform more repetitions as compared to the 10% VL threshold protocol. When comparing the repetitions performed between the 20% and 10% VL threshold protocols, the 20% protocol saw participants ‘most likely’ perform more repetitions. Changes in the number of reps performed over the 5 sets showed very large individual differences in the 10% VL threshold protocol, small individual differences in the 20% VL threshold protocol, and moderate individual differences in the 30% VL threshold protocol (b. Weakley et. al., 2019). These findings point to reduced kinematic and kinetic outputs when using larger VL thresholds, which has been demonstrated to impair adaptations in 1RM strength (Gonzalez-Badillo et. al., 2014). This also points to individual differences in work capacity and neuromuscular fatigue accrual during training as demonstrated by the variation in rate of VL within a working set.

Pareja-Blanco et. al. (2016) analyzed the changes in muscle structure and functional changes between two resistance training (RT) programs which utilized differing VL threshold protocols. The study participants consisted of twenty-four physically active men who were sport science student with 1.5-4 years of experience with RT and familiarity with the squat exercise. Participants went through an 8-week progressive RT program which consisted of two sessions per week for a total of 16 sessions where only the squat exercise was performed, and sessions were performed 48-72 hours apart. The study consisted of two randomized groups, a 20% VL threshold group and a 40% VL threshold group, who performed all training at the same %1RM. Squats were performed in on a smith machine with a LPT (T-Force System, Ergotech, Murcia, Spain) to assess velocity variables. For each repetition of the squat the eccentric phase was performed at a mean velocity of 0.50-0.65 m/s while the concentric phase was performed at maximal intended velocity. During the pre- and post-test, a 1RM was established following a progressive loading protocol which started a 30 kg followed by 10 kg increment increased until a MPV of less than 0.60 m/s was obtained. Once MPV dropped below this threshold, incremental increases of 2.5-5 kg were made until a 1RM was determined. While working up to a 1RM, three repetitions were performed for loads ≤ 50% 1RM, two repetitions for loads 50-80% 1RM, and one repetition for loads >80% 1RM. Rest between sets consisted of 3 minutes for light to moderate loads and 5 minutes for loads greater than 80% 1RM. The repetition with the greatest MPV at each load was used for establishing each participants load-velocity profile. In addition to the 1RM test, 3 velocity variables were used to analyze the how the two VL threshold protocols impacted the load-velocity relationship from pre- to post. The following velocity variables used included: average MPV attained at all absolute loads common to pre and post, average MPV attained at absolute loads common to pre and post that possessed velocity > 1 m/s, and average MPV attained at absolute loads common to pre and post that possessed velocity < 1 m/s. In addition to the 1RM testing, explosive force production was assessed utilizing the CMJ and 20-m sprint. Participants performed two maximal 20-m sprints which were timed using Photocell timing gates with 3 minutes rest between attempts. The best time between the two trials was kept for analysis. Utilizing an infrared timing system (Optojump, Microgate, Bolzano, Italy) jump height from five CMJ trials were analyzed with the highest and lowest jump heights discarded and the resulting average coming from the remaining 3 trials. In addition, muscle biopsies and MRI scans were taken assess potential fiber type and muscle cross-sectional area changes as a result of the 8-week RT. The RT program consisted of a standardized warm up between both groups prior to performing the squat exercise. For the 8-week duration of the RT, the number of sets, %1RM, and inter-set rest were identical between the two groups with a progressive increase in %1RM from 70-85% 1RM. However, the degree of neuromuscular fatigue accrued during each set varied between the two groups as measured by the magnitude of velocity loss within each set. Participants performed 3 sets with 4 minutes of inter-set rest. Each session, a target MPV was set and used as an estimation of the targeted %1RM based on the very close load-velocity relationship that has been previously established in prior studies (Gonzalez-Badillo & Sanchez-Medina, 2010; Sanchez-Medina et. al., 2014). The targeted MPV was to be attained on the first repetition of the first set, with the absolute load being individually adjusted to match the MPV correlated to the targeted %1RM for the given session. Following the 8-week RT, the 20% VL threshold group saw a 9.5% increase in CMJ height ($p < 0.001$) while CMJ height remained unchanged in the 40% VL threshold group ($p <0.07$). Both groups (20% VL and 40% VL threshold) saw statistically significant increases in 1RM strength (18% and 13.4%), average MPV attained at all absolute loads common to pre and post (12.5% and 6.0%), and average MPV attained at absolute loads common to pre and post that possessed velocity < 1 m/s (21.7% and 13.7%). The 20% VL threshold group saw a statistically significant improvement in average MPV attained at absolute loads common to pre and post that possessed velocity > 1 m/s (6.2%, $p < 0.01$) while the 40% VL threshold group remained unchanged (+1.0%, $p = 0.62$). Sprint running performance saw no statistically significant changes in either group. Over the duration of the 8-week RT, the 40% VL threshold group performed more repetitions ($p < 0.001$) than the 20% VL threshold group while the 20% VL threshold group trained at significantly faster MPV as compared to the 40% VL threshold group (0.69 ± 0.02 vs. 0.58 ± 0.03 m/s; $p <0.001$). These findings are of particular interest in regard to the application of VBT for strength and conditioning practitioner as they point to greater improvements in key performance indicators (KPI) while training at significantly less volume (Pareja-Blanco et. al., 2016).

2.8 Validation of VBT Devices

2.8.1 Validation of LPTs

LPTs to this point have generally been shown to possess the greatest accuracy when measuring MCV as compared to more novel VBT devices such as IMUs and laser optic encoders. LPTs such the GymAware, T-Force, Open Barbell System, and Tendo Fitrodyne have been tested and compared to 'true' gold standards such as 3D high-speed motion-capture systems or force platforms (Weakley et. al., 2021). However, the GymAware has provided the greatest accuracy when these LPT devices have been directly compared during free-weight exercise (Weakley et. al., 2021). LPTs work to directly measure velocity through a retractable tether and spool system where the tether is directly attached to the system (barbell or athlete if performing a jump) while sensor at the base of the spool measures change in displacement of the tether as it leaves the spool. The GymAware possesses a distinct feature as compared to other LPTs in that the sensor considers the angle of the movement which allows for greater accuracy in the measurement of the vertical-only displacement using trigonometry to correct for any horizontal displacement (Wadhi et. al., 2018). The GymAware PowerTool collects data and utilizes a variable rate sampling method where the encoder provides a single electrical impulse for every three millimeters of displacement which is then time stamped with a one-millisecond resolution. To reduce noise associated with the high frequency sampling the encoder down samples to a sampling rate of 50Hz and data is then transmitted via Bluetooth to a tablet (Weakley et. al., 2019b). An LPT predicts KPI's such as power and rate of force development (RFD) through a direct measure of displacement while utilizing a time stamp to determine the duration to ultimately calculate velocity. Kinetic values are further predicted from the calculated velocity by entering the mass of the system into the software. Acceleration is calculated through the velocity changes over the duration of the movement. From this point force can be predicted by multiplying the calculated acceleration with the mass that was manually entered into the software. Power is then calculated by multiplying the predicted force value by the velocity value attained by the encoder.

A study by Wadhi and colleagues (2018) performed a novel study to assess the test-retest reliability and concurrent validity of the GymAware when assessing the CMJ and squat jump (SJ) (Wadhi et. al., 2018). The study consisted of 28 participants with a varying degrees of training age ranging from 6 months to more than a year. The age of participant varied as well with ages ranging from 19-47 years of age with only 18 subjects returning for the second day testing. Of the 18 returning subjects the average age was 22.11 ± 2.22 years of age. The jump assessment protocol between the two sessions were identical, consisting of the participants performing a standardized treadmill warm up before being weighted on the force plate and having the GymAware attached to a waist belt which was worn just above the iliac crest. Participants performed 3 SJ jumps followed by 3 CMJs both of which started in an upright standing position and maintained hand placement at the hips throughout the duration of the jumping motion. The CMJs were performed by the participants after receiving a single "jump" command where the participants lowered to a self-selected half squat depth followed by an immediate maximal effort jump with the intent to maximize jump height. The SJs were performed by the participants after receiving two commands. The first command being "set" which instructed the participant to lower to a self-selected half-squat depth followed by a 3 second pause of the position before being instructed to "jump" which was followed by a maximal effort jump with the intent to maximize jump height without dipping. 30 second rest intervals were given between jump trials (Wadhi et. al., 2018). An AMTI AccuPower force plate (Advanced Mechanical Technology Incorporated, Watertown, MA, USA) served as the criterion device which utilizes the Hall effect to measure forces across all six axes over a duration of 6 seconds with a sampling rate of 1200Hz (Wadhi et. al., 2018). The AccuPower 2.0 software analyzes the vertical component of the ground reaction force (GRF) and estimates the concentric impulse and the take-off velocity through the impulse-momentum theorem. Jump height is then calculated from the estimated take-off velocity ($h = v^2/2g$, where h represents jump height, v represents take-off velocity, and g represents the acceleration due to gravity). The highest jump values retrieved from the GymAware for each participant from day 1 and day 2 were used for the statistical analysis. A paired two-tailed t-test with 95% confidence intervals (CI) were used to assess the concurrent validity of the GymAware to check for differences between the LPT system and the force plate with an additional Bland-Altman analysis to check for variance in the day 1 and day 2 values. Intraclass correlation coefficient (ICC) was used to assess the reliability of the GymAware. The results from the paired t-test demonstrated a statistically significant difference in both the SJ ($p<0.001$) and CMJ ($p<0.001$) between the GymAware and the force plate. A systematic overestimation of jump height in both the CMJ and SJ was revealed with a mean difference of 8.68 cm and 8.01 cm, respectively. These results are in agreement with a similar study conducted in 2017 by O'Donnell et. al., which assessed CMJ in female athletes and demonstrated an average overestimation of 7 ± 2.4 cm in jump height. Despite overestimating jump height, the GymAware demonstrated good consistency in both jumps across days. The CMJ possessed excellent test-retest reliability (ICC=0.95) and low variability between days (CV=0.74%) while the SJ possessed good test-retest reliability (ICC=0.84) and low variability between days (CV=3.24%) with the 'gold standard' force plate demonstrating a similar variability in the two jumps (CMJ: CV=0.33%; SJ: CV=0.33%). While the overestimation of jump height denies the GymAware of validity for accurately measuring jump height for testing, its reliability makes the LPT a good option for monitoring neuromuscular fatigue for strength and conditioning coaches and practitioners.

A study by O'Donnell et. al. (2017) assessed the validity and reliability in CMJ jump height, PV, and MV between the GymAware LPT and the Dual-Axis Force Platform (Pasco, California, USA). Participants wore a waistbelt with the GymAware tether attached while standing on the force plate allowing for both devices to simultaneously measure jump height. Validity was measured using 27 recreationally trained females, who performed 3 CMJs. Reliability was measured separately using 11 elite female athletes who performed 3 CMJs on 3 separate days. All jumps were performed 48 hours apart and at the same time of day to account for diurnal variation. Validity was assessed through Pearson correlation coefficient and typical error of estimate. Jump height between the two devices possessed a correlation of 0.9 with a typical error of estimate of 2.3 cm. Results demonstrated the GymAware overestimated jump height with a mean bias of 7.0 ± 2.8 cm (O'Donnell et. al., 2017). Reliability was assessed through ICC and CV. Results demonstrated the GymAware possessed a high mean ICC for PV and MV (0.90 and 0.91, respectively). ICC values were slightly lower for jump height with a mean ICC of 0.70. All three measurements produced low CV values with jump height, PV, and MV producing values of 6.2%, 4.7%, and 6.7%, respectively (O'Donnell et. al., 2017). Results would indicate the GymAware proves to be a valid measure of CMJ jump height with a overestimation measurement bias. The GymAware demonstrated reliable test-retest measures for all three measurements.

2.8.2 Validation of IMUs

The utilization of IMUs for monitoring changes in neuromuscular performance and fatigue has grown over the past decade in effort to serve as a viable cost efficient and portable option to LPTs. While a sizable amount of literature exists looking at the validity and reliability of IMUs, their accuracy and reliability of IMUs use in strength and conditioning is inconclusive as most of the studies did not utilize gold standard criterion when assessing validity. A recent systemic review by Weakley et. al. (2021) demonstrated that 23 studies assessed validity of various IMU devices (Push Band version 1.0 and 2.0, BarSensei, Beast sensor, and Myotest) while 14 studies quantified the reliability of various IMU devices. Of these studies only 10 have directly compared IMUs to gold standard criterion such as force plates or 3D motion capture systems with exercises such as back squat, ballistic squat, bench press, deadlift, shoulder press, and the biceps curl. Of the studies comparing IMUs to gold standard criterion the methods vary greatly as some studies utilize a smith machine while others utilize free weight. The utilization of the smith machine in these studies lessen the transfer of the findings to the field of strength and conditioning as the smith machine removes the horizontal displacement of the movement through a fixed bar path. However, studies assessing the validity of popular IMU units in free weight back squats have yielded mixed results.

A study by Abbott et. al. (2020) looked to evaluate the kinematic variables produced by the BarSensei IMU (Assess2Perform, Steamboat Springs, CO, USA) in the free weight back squat exercise against a Vicon 3D motion capture system (4 cameras, Vicon System, Nexus 1.85, Vicon Motion Systems, Oxford, UK). Participants consisted of 16 resistance trained males who came in for a single session to perform a 1RM squat protocol. Subjects performed a self-selected warm up prior to beginning the 1RM squat protocol which began with 2 repetitions at 20% of self-reported 1RM. Following sets consisted of 2 repetitions with 10% load increment increases up until 70% of self-reported 1RM was reached. Once 75% 1RM was reached, one repetition sets were performed with 5% increases in load until technical or actual failure occurred (Abbott et. al., 2020). The inter-set rest durations were self-selected times between 3-5 minutes.

Repetitions chosen for validation analysis consisted of all successful repetitions from 20%-100% 1RM. The 3D Vicon motion capture system was set at a sampling rate of 100Hz to match that of the BarSensei while both systems captured the following variables: eccentric peak velocity (EPV), eccentric mean velocity (EMV), MCV, and MPV. Data was grouped into four %1RM conditions, 20-39%, 40-59%, 60-69%, 70-100%. A 2x4 repeated measure ANOVA test was completed for each variable to determine any differences between the two devices which indicated no significant differences between subjects or devices for CMV, EPV, EMV while MPV measures possessed a significant interaction of device ($p<0.01$) and intensity with no between-subject effect. Further testing using a Bonferroni post hoc analysis showed no significant difference between devices for MPV ($p<0.23$). Significant interaction ($p<0.01$) and between-subject effects ($p<0.01$) were found with PCV (Abbott et. al., 2020). Further testing using a Bonferroni post hoc analysis revealed significant differences ($p<0.01$) between devices. A significant difference for PCV between devices at intensities greater than 40%1RM (40-69%: $p<0.01$; 70-100%: $p<0.01$) was revealed by simple main effects. Small differences in PCV were observed with intensities less than 60%1RM (d= -0.16-0.55) as well as for MCV greater than 60%1RM (d= -0.16-0.57). This particular study demonstrated the BarSensei IMU to lack validity as SEE demonstrated a large error for PCV values when intensities were greater than 60%1RM. Reliability was void in addition as the magnitude of coefficient of variation increased in MCV and PCV at a greater rate in the IMU as compared to the motion capture system (Abbott et. al., 2020).

A study by Banyard and colleagues (2017) looked to assess the validity both the GymAware LPT and Push IMU using a force plate (AMTI BP6001200, Watertown, MA, USA) as the gold standard criterion. Ten resistance trained males (>6 months experience) that could perform a full back squat with at least 1.5 times body weight. Participants performed an initial 1RM trial to establish 1RM to accurately predict %1RM loads in the following two data collection trials. The following two trials were separated 48 hours apart and consisted of two incremental 1RM back squat assessments with all three systems collecting data every repetition (Banyard et. al., 2017). A standardized warm up was performed in the 2nd and 3rd trials before beginning the incremental 1RM back squat assessment. The back squat protocol consisted of performing three repetitions at 20, 40, and 60% of 1RM followed by a single repetition at 80, 90, and 100% of 1RM. A maximum of five 1RM attempts were allowed following successful 1RM attempts. Weight increases between 1RM attempts ranged from 0.5 kg- 2.5kg. Inter-set recovery times were 2 minutes between warm-up sets and 3 minutes between 1RM attempts (Banyard et. al., 2017). The Push IMU was placed on the right forearm just below the elbow crease as suggest by the manufacturer. Data obtained from the Push was recorded at a sampling rate of 200Hz while the GymAware utilized variable rate sampling and then down sampled to 50Hz for analysis.

> *'The Push determines velocity by measuring linear accelerations and angular velocities of the movement where vertical velocity was calculated by the integration of acceleration with respect to time. (Banyard et. al., 2017)'*

The triaxial IMU estimates force values by multiplying the systems mass by the acceleration data while power values are estimated from the product of the estimated force values and the measured velocity values. The variables assessed for accuracy between the device systems included MCV, PCV, mean concentric force (MCF), peak concentric force (PCF), mean power (MP), and peak power (PP). The two field-based devices were only deemed highly valid if they met the following criteria: very highly correlated (>0.70), moderate CV (≤10%), and a small effect size (<0.60) (Banyard et. al., 2017). A repeated measures ANOVA with α=0.05 and confidence intervals set at 95% was used for the statistical analysis. The results showed the GymAware was highly valid for all criterion variables while the Push was only valid for PCF. The GymAware met the criteria for validity across all relative loads for PCF, MCF, PCV, and MCV while the Push IMU failed to meet criterion validity in MCV at ≥80% 1RM, PV >20% 1RM, MCF ≤90% 1RM, MP at 40% 1RM and above, and PP at all relative intensities (Banyard et. al., 2017).

Lake et al. (2018) looked to assess the validity of the velocity and power variables produced by the belt-worn Push IMU when performing a CMJ as compared to laboratory-based gold standards. Twenty-two healthy participants who regularly participated in university-level sports completed came in for a single session which consisted of a standardized warm up followed by 3 CMJ with a minute rest between attempts. CMJs were performed with hands placed on the hips throughout each jump to remove impact of arm movement. All jumps were performed on a force platform (Kistler Type 9287C, Kistler Instruments, Hampshire, UK) with concurrent data collection through the Push IMU and a 10-camera 3D motion capture (Vicon T40S, Vicon Motion Systems, Oxford, UK). A single reflective marker was placed was attached directly over the belt-worn Push IMU sensor. MCV, PCV, MP, and PP values from the propulsion phase of the jump were analyzed by the three systems. Data analysis was calculated for all three trials with the trial possessing the highest peak velocity being used for further analysis for validity. Within-session reliability was assessed by comparing the data from the trials with the two highest peak velocity values. Statistical analysis showed the Push IMU tended to overestimate PCV by 0.447 m/s (SEM= 4.2% of force plate PCV, r = 0.826, CV= 5.7%, Mean Difference = 0.068 m/s) and overestimate MCV by 0.340 m/s (SEM= 5.4% of force plate MCV, r = 0.704, CV= 5.4%, Mean Difference = -0.147 m/s). The Push IMU tended to underestimate PP by 1764 W (SEM = 13.3% of force plate PP, r =0.704, CV=15.4%, Mean Difference = 691 W) and MP by 938 W (SEM= 16.4% of force plate MP, r= 0.621, CV= 18.3%, Mean Difference = 502 W). The Push band demonstrated reliability; however, it possesses the tendency to systematically overestimate velocity variables and should not be used to measure power variables.

The VmaxPro (Blaumann & Meyer-Sports Technology UG, Magdeburg, Germany) is a novel IMU device that has yet to be extensively assessed for its validity or reliability. Currently, only three independent study have been published with the purpose of validating the device, which tested the IMU for criterion validity against either an LPT device or 3D motion capture.

Held and colleagues (2021) analyzed the validity and reliability of MCV and displacement values measured by the VmaxPro IMU against the Speed4Lift LPT (Madrid, Spain). 19 males (23.1 ± 3.2 years) with a minimum of 2 years resistance training experience participated in this study, which utilized a randomized controlled crossover design. Participants competed a familiarization trial where they were accustomed to the procedures, exercises, and equipment and were asked to avoid any strenuous activity in the 24-48 hour window prior to each testing session. The study entailed four visits which consisted of a familiarization trial, a 1RM testing trial, and two visits which assessed validity and reliability. The first two visits were 48-72 hours apart and the final two visits were performed a week apart. A standardized protocol was used which consisted of 5 minutes of self-selected stretching followed by 2 warm up sets consisting of a set of 10 repetitions at 40% 1RM and a set of 5 repetitions at 60% 1RM. The familiarization session consisted of 3-4 sets of squats performed with approximately 60% 1RM. The second session consisted of an incremental 1RM test of the back squat exercise. The third and fourth sessions consisted of 30 total repetitions (3-5 sets at 75% 1RM with 3 minutes rest) with the participants encourage to perform the concentric phase of the movement with maximal intended concentric velocity. Data was collected from both devices which were attached to the barbell. The LPT collected displacement data with respect to time utilizing a sampling rate of 1000Hz while the IMU collected data through the integration of the vertical acceleration with respect to time utilizing a sampling rate of 1000Hz. All reps performed at 75% 1RM from the 3rd and 4th session were used for validity testing with only the first two sets of both sessions being used for within- and between-day reliability analyses. As a result, the repetitions that possessed the greatest MCV and displacement from the first 3 reps of the first two sets were analyzed. Multiple one-way repeated measures ANOVAs were used to analyze the two outcome measures (MCV and displacement). In addition, multiple 2x2 repeated measure ANOVAs were performed for MCV and displacement. Bonferroni post-hoc tests were computed if significant effects were detected. Post-hoc testing revealed a significantly ($p<0.001$) lower MCV for the IMU (0.52 ± 0.12 m/s) as compared to the LPT (0.53 ± 0.12 m/s). Post-hoc testing revealed a significantly ($p<0.001$) lower displacement for the IMU (55.5 ± 9.2 cm) as compared to the LPT (58.8 ± 9.5 cm). VmaxPro MCV showed good ICC values for within-day (ICC= 0.88) and between-day (ICC= 0.82) reliability. The results of this study indicate that the VmaxPro is a valid and reliable tool when compared to the Speed4Lift LPT for assessing MCV.

A recent study by Menrad & Edelmann-Nusser (2021) tested the validity of three VBT devices against a 12-camera Vicon motion capture system to evaluate each devices performance in measuring MCV. The three devices analyzed included: GymAware (LPT), Push (IMU), and VmaxPro (IMU). The study consisted of 12 subjects with at least 2 years of previous resistance training experience and having performed strength training at least once a week for the previous year. Each participant's 1RM in the deadlift, squat, and barbell row were determined before their single visit. During the single visit, participants completed three sets of each exercise with the first and second sets consisting of 10 repetitions at 40% and 60% 1RM loads (Menrad & Edelman-Nusser, 2021). In the third set, a load of 80% 1RM was used and participants were instructed to complete the set one repetition shy of technical failure. The Vicon motion capture was used as the gold standard reference. Data for the 3D motion capture system was recorded at a frequency of 200 Hz on the Vicon Nexus 2.10 software with four retroreflective markers, 2 placed at the endcaps of the barbell and 2 placed opposites of one another on the shaft of the barbell (Menrad & Edelmann-Nusser, 2021). The GymAware system's cable was attached to the shaft of the barbell nearest the collar while the Push IMU and VmaxPro were placed to the left and right of the 2 retroflective markers. All three VBT systems collected data utilizing their corresponding manufacturer software. Data was collected from the three devices at the following frequencies: 50 Hz (GymAware), 200 Hz (VmaxPro), and 1000 Hz (Push). Linear regressions for the MCV per repetition of the 3 systems were plotted against the MCV per repetition of the Vicon 3D motion capture. Linear regressions were plotted with MCV of all three exercises as well as each exercise separately. The systems were further compared via Bland-Altman diagrams (Menrad & Edelmann-Nusser, 2021). Push demonstrated the largest coefficient of determination (R^2) for all exercise combined (R^2=0.8758), squat (R^2=0.9583), barbell row (R^2=0.8857), and deadlift (R^2=0.831). While the GymAware and VmaxPro both demonstrated better results: all exercises combined (R^2=0.9825; R^2=0.9835), squat (R^2=0.9962; R^2=0.9848), barbell row (R^2=0.9797; R^2=0.9759), and deadlift (R^2=0.9822; R^2=0.9854). Push again demonstrated the largest variance of the three devices with differences between the upper and lower Limits of Agreement (LoA) for all exercises combined (0.272), squat (0.143), barbell row (0.284), and deadlift (0.335). The VmaxPro demonstrated the smallest amount of variance with difference between upper and lower LoA of 0.085 for all exercises combined followed closely by the GymAware with a difference of 0.112 (Menrad & Edelmann-Nusser, 2021). The results of this study indicate that the GymAware and VmaxPro systems provide valid results when determining MCV of the squat, barbell row, and deadlift exercises while the Push system possessed noticeably higher levels of variance indicating that the Push system may not be fully valid.

A study produced by Fritschi et al. (2021) assessed the validity of multiple VBT training devices. The aim of the study was to assess and compare the validity of MCV and PCV of the following devices: GymAware (LPT), 1080 Quantum (LPT), VmaxPro (IMU), Push (IMU), and the Flex (laser optic encoder). In addition, all repetitions were collected with an eight camera Vicon 3D motion capture system with 6 reflective marker placements were used to establish the criterion validity data. In order to assess the velocity values over a wide range of velocities in free-weight exercises, the study included the following exercises: hang power snatch, back squat, loaded CMJ, and loaded SJ. The study consisted of 14 participants with a varying range of free-weight training experience where each participant performing 1-2 sets of 5 repetitions. Following the warm-up, participants performed several repetitions of back squat with a self-selected load that they perceived to be light to moderate. Additional warm-up sets were performed with load increments of 5-20kg at maximal voluntary concentric speed while having barbell velocity tracked by GymAware to determine loads with a MCV of 0.7-0.8m/s and 0.5m/s to later be used for their main measures (Fritschi et. al., 2021). The hang snatch exercise was performed with a standardized weight of 20kg while back squats were performed at both moderate weight (0.7-0.8m/s) and heavy weight (0.5m/s) which was established during the warm-up. Both the CMJ and SJ were performed with approximately 50% of the load used for the moderate back squat. For data collection both the Push and VmaxPro were placed on the shaft of the barbell on separate ends near the collar while the Quantum 1080 had both cables attached to the barbell sleeve. The GymAware was attached to the shaft of the barbell nearest the collar while the Flex was placed on the endcap on the barbell on the right side. The criterion parameters (MCV & PCV) were generated from the data collected by the 3D motion capture where each repetition and reflective marker attachment point were analyzed. The concentric phase of the squat and jump movements were identified by the vertical velocity onset-threshold of 0 m/s while 0.5m/s was used for the hang power snatch (Fritschi et. al., 2021). The end of the concentric phase for all exercises was recognized by a threshold of 0 m/s after the concentric phase was identified. In order to recognize erroneous criterion data points a linear regression relating all device data and criterion data on all repetitions was ran where all repetitions that possessed standardized residuals greater than 2 were thrown out, resulting in the exclusion of approximately 5% of all repetitions performed (Fritschi et. al., 2021). The validity of the MCV and PCV produced by each VBT device was assessed using a Pearson's correlation coefficient (r) and standard error of estimate (SEE) to assess precision while a calibration equation was used to assess accuracy of measurement. When analyzing the precision of the five devices' PCV, they ranked as follows: Quantum (r=1.00; SEE=0.07m/s), GymAware (r=0.99; SEE= 0.08m/s), VmaxPro (r=0.99: SEE=0.11m/s), Flex (r=0.96; SEE=0.18m/s), and Push (r=0.98; SEE=0.15m/s). When analyzing the precision of the five devices' MCV, they ranked as follows: GymAware (r=0.99; SEE=0.06m/s), VmaxPro (r=0.99; SEE=0.08m/s), Quantum (r=0.97; SEE=0.12m/s), Flex (r=0.96; 0.12m/s), and Push (r=0.97; SEE=0.12m/s). The results of the following study point toward the VmaxPro displaying the ability to produce high precision in measuring MCV and PCV in exercises across various velocity ranges.

On the manufacturer's website, VmaxPro provides their in-house pilot studies to provide potential customers with some form of criterion validation. The following studies looked at the bench press, back squat, and deadlift exercises with two VmaxPro IMU sensors placed on opposite sides of the barbell with four Vicon markers placed near the two IMU sensors. A 13-camera Vicon Nexus 2.4 3D motion capture analysis was utilized as the gold standard. Participants consisted of 3 athletes with moderate to extensive experience in powerlifting. The company's bench press study demonstrated a distance deviation of -0.35 ±1.54 cm, -0.45 ±1.05 cm/s difference in MCV, and -0.53 ±1.51 cm/s difference in maximum velocity (Vmax) when compared to the Vicon camera system. The between device reliability testing showed a distance deviation of -0.27 ±0.62 cm, -0.49 ±0.89 cm/s for MCV, and -0.73 ±1.54 cm/s for Vmax. The company's deadlift study demonstrated a distance deviation of -0.46 ±1.35 cm, -0.28 ±0.96cm/s for MCV, and -0.94 ±1.55 cm/s for Vmax when compared against the Vicon camera system. The between device reliability testing showed a distance deviation of 0.07 ±0.92 cm, -0.08 ±0.81 cm/s for MCV, and 0.29 ±1.30 cm/s for Vmax. The company's back squat study demonstrated a distance deviation of -0.54 ±2.05 cm, -0.84 ±1.47cm/s for MCV, and -0.35 ±1.96 cm/s for Vmax when compared against the Vicon camera system. The between device reliability testing showed a distance deviation of -0.14 ±1.15 cm, -0.52 ±1.10 cm/s for MCV, and -0.19 ±1.42 cm/s for Vmax (company website: https://vmaxpro.de/).

2.9 Summary

The current research supports the utilization of velocity as a means to prescribe and monitor training load, but the current evidence of utilizing IMU devices to accurately assessing performance values for the detection of various performance adaptations is questionable. The validity of various performance values differs and demonstrates inconsistency from come manufacturer to manufacturer. More research is needed to find proper strategies to employ the technology and discover the limitations of these devices. This thesis will look to address the validity of a novel IMU device and explore potential limitations that exist allowing for further clarification of the device's capabilities. Furthermore, this thesis will contribute to the body of literature evaluating the validity of the application of IMU devices in measuring performance metrics, which will be of value for strength and conditioning practitioners.

CHAPTER III – METHODOLOGY

3.1 Participants

A total of 25 recreationally trained participants were recruited from the University of Southern Mississippi (USM) and surrounding communities to participate in a study validating the use of the VmaxPro IMU device for measuring performance related variables. Participants were recreationally trained, defined as possessing the ability to perform a full back squat with at least 1.5 times their body mass and having performed resistance training at least twice a week for the past 6 months. The study comprised of male and female participants between the ages of 18 and 35 years. Each participant voluntarily attended one testing session with a total duration of 60 minutes. Inclusion criteria consisted of prior experience performing the back squat movement which was confirmed by way of questionnaire.

Participants were excluded from the study if any of the following exclusion criteria were present: current or previous cardiovascular, metabolic, or neurological disease, currently pregnant, presence of lower back pain, musculoskeletal injury, prior injury in the past 6 months, or current collegiate or elite athlete.

Each participant was provided with verbal instruction for pre-testing procedures. Participants were required to refrain from vigorous activity for 24 hours prior and any strenuous lower body activity 48 hours prior to testing. Participants were instructed to refrain from alcohol consumption 24 hours prior to testing as well as caffeine 8 hours prior. The aforementioned pre-exercise instructions were confirmed at the start of each session via questionnaire. Participants who did not meet the aforementioned criteria were asked to reschedule for another session.

3.2 Recruitment and Screening Procedures

All procedures of the present study, including recruitment strategies, were approved by The University of Southern Mississippi Institutional Review Board (IRB) 21-176. Recruitment was conducted by verbal presentations by the investigator to classrooms within the School of Kinesiology and Nutrition at USM. Prospective participants were provided a questionnaire to address the above-mentioned inclusion and exclusion criteria (Appendix A). Upon completion of the questionnaire, eligible participants were asked to provide available dates for the single testing session.

3.3 Experimental Design

The present study was based on a sample size calculation determined via G*Power (Version 3.1, Faul, 2007) which produced a required total sample size of 24 participants (α=0.05, Power=0.80, effect size=0.6). A total of 25 participants were recruited for the study in order to account for any potential attrition or erroneous data collected during the single testing session. The study was constructed with a within-subjects randomized parallel design. Each participant was subjected to three intensity conditions of the back squat and performed the counter movement jump. The correlation and agreement in performance variables were determined between two devices.

Conditions of back squat intensity were randomized for each participant. All participation was considered voluntary and participants retained the right to withdraw at any point without penalty.

Upon arrival to the School of Kinesiology and Nutrition Biomechanics Laboratory in Joseph Greene Hall at USM, each participant was asked to complete an informed consent for volutary participation in the study. The informed consent forms contained the purpose of the study, all risks and benefits of participation, and a right to withdrawl without penalty statement. Following consent, participants were asked to complete a pre-exercise questionnaire which included a PAR-Q+ with the addition of information regarding additional health status and estimated 1RM back squat load. Pre-exercise health risk stratification was conducted by using the results of the PAR-Q+, as recommended by the American College of Sports Medicine (2017). Particiapnts who were stratified as low risk proceeded into the testing session. Participants who classified as moderate risk or above thus requiring medical clearance to perform physical activity were excluded from participation. Participants were subjected to an approximate 60-minute testing session. The single testing session for all participants began with a 10-minute familiarization where all equipment, procedures, and movement techniques were introduced. Any discrepancies in movement techniques was addressed on an individual basis prior to the commencement of testing. Upon completion of familiarization, test measures began with anthropometric measures and a brief standardized lower-body warm-up. Once completing the warm-up, participants performed counter-movement jump trials. The back squat trials were performed next in a randomized order. Each of these measures is explained in the following sections.

3.4 Experimental Measures

The present study included the following experimental measurements; anthropometrics (height, weight), CMJ jump height, CMJ depth, CMJ mean concentric velocity, CMJ mean concentric power, CMJ duration, back squat displacement (depth), back squat mean concentric velocity, back squat mean concentric power, back squat duration and back squat displacement (depth). The CMJ measures were collected prior to a randomized order of the following back squat conditions: bodyweight back squat, 50% bodyweight back squat, and 100% bodyweight back squat. Randomization of the back squat conditions were computer generated. All raw force plate and Vmaxpro IMU data for the countermovement jump were processed with a custom excel macro as described by Chavda et. al., (2018). The custom excel macro was used to identify key phases of the CMJ and derive the variables from their corresponding phases. The countermovement jump consists of six phases: (1) weighing phase, (2) unweighting phase, (3) braking phase, (4) propulsion phase, (5) flight phase, and (6) landing phase. Prior to collection, the force plate was zeroed before the participant was instructed to step onto the force plate. The weighing phase took place as the participant stood motionless in a ready position for one second, where bodyweight was collected by averaging the time domain force values (Chavda et. al., 2018). The unweighting phase, which represents the start of the jump, was identified as the first force value that was less than 5 standard deviations of the participant's previously averaged bodyweight (N) value. At this point a force value that was less than the participant's bodyweight was obtained in addition to a velocity value of less than zero (Chavda et. al., 2018). The unweighting phase was identifed as the point when the vertical ground reaction force reached a value equal to the bodyweight (N) of the individual. This was also identifed as the lowest attained velocity which corresponded to the end of the negative acceleration associated with this phase (Chavda et. al., 2018). Following the unweighting phase, the breaking phase was identifed by the increase in force past the participant's bodyweight (N) and a velocity value increase to zero (McMahon et. al., 2018). The propulsive phase was identifed as the moment postive velocity occurred following the zero velocity value attained during the breaking phase. The flight phase was identifed as the take-off point, which was identified in excel by identifying the smallest force value that is less than or equal to 10 N (Chavda et. al., 2018). Throughout the duration of the flight phase, the force value was equal to zero. During the flight phase, velocity decreased to a point at which zero velocity occurred, identifying the point at which peak displacement had occurred (Chavda et. al., 2018). The landing phase corresponded with the rapid onset of increasing force values. The landing point was identified as the first value greater than 10 N between peak displacement and peak landing force (Chavda et. al., 2018). Key variables derived from the raw force data included acceleration, velocity, displacement, and power. Acceleration was calculated by dividng the force by the athlete's mass. Velocity was then integrated from acceleration by adding the initial velocity to the product of acceleration and time ($V = v_i + at$) (Chavda et. al., 2018). Displacement was then obtained by integrating velocity which was achieved by taking the difference between initial velocity and final velocity and multiplying it by the time interval between initial and final velocity and dividing it by two ($s = \frac{1}{2}(v_f - v_i)t$). The final variable of interest was power, which is solved for by multiplying velocity by force with respect to the associated time stamp ($P = F\ x\ v$).

Sampling frequency was converted from hertz (Hz) to time (s) to represent how many data points were collected within a 1 second time frame (Chavda et. al., 2018).

All raw force plate and Vmaxpro IMU data were processed for the back squat with a custom excel macro utilizing the equations as described by Cormie et. al., (2007) and Chavda et. al. (2018). The vertical ground forces obtained from the force plate were used to determine acceleration by dividing force by the system mass at each instantaneous time point (i), $a_{(i)} = \frac{F_{(i)}}{SM}$. To guarantee that only the acceleration produced by the subject was used to determine velocity, the acceleration due to gravity was subtracted from all calculated accelerations (Cormie et. al., 2007). The product of acceleration and time data at each time stamp was used to calculate the instantaneous vertical velocity of the system, $v = \Delta a * \Delta t$. Power was then calculated by multiplying the measured force values from the derived velocity data ($P = F * v$). Displacement was then obtained by integrating velocity which was achieved by taking the difference between initial velocity and final velocity and multiplying it by the time interval between initial and final velocity and dividing it by two ($s = \frac{1}{2}\left(v_f - v_i\right)t$) (Chavda et. al., 2018). The acceleration data from the Vmaxpro IMU was processed with the same excel macro but set up to solve for force, velocity, and displaement from the acceleration values. Instantaneous velocity values were integrated from acceleration by taking the product of acceleration and time data at each time stamp, $v = \Delta a * \Delta t$ (Cormie et. al., 2007). The mass of the system was manually put into the excel macro which was then used to calculate force values for each time stamp. Force was calculated as the product of the system mass and acceleration value of the respective time stamp. Power was then calculated by multiplying the force values by the derived velocity data ($P = F * v$) (Cormie et. al., 2007). Displacement was obtained by integrating velocity which was achieved by taking the difference between initial velocity and final velocity and multiplying it by the time interval between initial and final velocity and dividing it by two ($s = \frac{1}{2}(v_f - v_i)t$). Sampling frequency was converted from hertz (Hz) to time (s) to represent how many data points were collected within a 1 second time frame (Chavda et. al., 2018).

3.4.1 Anthropometric Measures

Anthropometric measures such as height and weight were obtained. Height was measured with shoes off on a standard stadiometer. Weight was measured with shoes on while standing still on the force plate.

3.4.2 CMJ Condition

Participants completed a brief warm-up consisting of dynamic lower body movements (i.e. leg swings) and 3 submaximal countermovement jumps. The countermovement jump was be performed with a PVC dowel (1.0 kg) placed across the shoulders in a high bar position while standing on the force plate for data collection. The IMU was placed on the right side of the dowel facing upright. Participants performed 3 sets of 1 repetition at a self-selected foot position and to a self-selected depth. Each participant was instructed to "jump as high as possible" while maintaining constant contact between the PVC dowel and their upper back through the duration of the movement. Prior to performing the countermovement jump, all participants were instructed to stand perfectly still prior to initiation of the movement to allow for the force plate to determine body mass which was then be used for calculating the variables of interest. Participants were then counted down using a “3, 2, 1, jump” command for each jump trial (Donahue et al., 2020).

3.4.3 Body Weight Back Squat Condition

Due to the randomization of the squat conditions, standardized warm-up sets of 3 repetitions were performed prior toconducting the test trial, with participants performing a single set of 3 repetitions across the following loads: 20 kg, 40 kg, and 60 kg. Participants were provided a 3 minutes rest between sets. The body weight back squat was performed with a PVC dowel (1.0 kg) placed across the shoulders in a high bar position while standing the force plate for data collection. The IMU was placed on the right side of the dowel facing upright. Participants completed 1 set of 3 repetition at a self-selected foot width and to a depth with which the hip crease obtained a position below the patella in the bottom position. Each participant was instructed to squat while maintaining constant contact between the PVC dowel and their upper back through the duration of the squat and without letting the heels leave the ground. Prior to performing each squat repetition, all participants were instructed to stand perfectly still prior to initiation of the movement to allow for the force plate to determine the mass of the system (dowel + human) which was then used for calculating the variables of interest. Participants were asked to come to a complete stop before being instructed when to perform the next repetition. The variables of interest included mean concentric velocity, mean concentric power, displacement, and duration. Mean concentric velocity and mean concentric power were calculated from averaging the instantaneous velocity and power values collected during the duration of the concentric phase. Displacement was calculated as the depth attained during the eccentric phase of the lift. Duration was collected as the time taken to perform the movement.

3.4.4 50% Body Weight Back Squat Condition

Due to the randomization of the squat conditions, standardized warm-up sets of 3 repetitions were performed prior toconducting the test trial, with participants performing a single set of 3 repetitions across the following loads: 20 kg, 40 kg, and 60 kg. Participants were provided 3 minutes rest between sets. The 50% body weight back squat was performed with a 20 kg barbell with weighted plates added to equate 50% of the participant's body weight. The barbell was placed across the shoulders in a high bar position while standing the force plate for data collection. The IMU was placed on the right side of the barbell same as previous. Participants completed 1 set of 3 repetitions at a self-selected foot width and to a depth with which the hip crease obtained a position below the patella in the bottom position. Each participant was instructed to squat while maintaining constant contact between the barbell and their upper back through the duration of the squat and without letting the heels leave the ground. Prior to performing each squat repetition, all participants were instructed to stand perfectly still prior to initiation of the movement to allow for the force plate to determine the mass of the system (barbell + human) which was then used for calculating the variables of interest. Participants were asked to come to a complete stop before being instructed when to perform the next repetition. The variables of interest included mean concentric velocity, mean concentric power, displacement, and duration. Mean concentric velocity and mean concentric power were calculated from averaging the instantaneous velocity and power values collected during the duration of the concentric phase. Displacement was calculated as the depth attained during the eccentric phase of the lift. Duration was collected as the time taken to perform the movement.

3.4.5 100% Body Weight Back Squat Condition

Due to the randomization of the squat conditions, standardized warm-up sets of 3 repetitions were performed prior toconducting the test trial, with participants performing a single set of 3 across the following loads: 20 kg, 40 kg, and 60 kg. Participants were provided 3 minutes rest between sets. The 100% body weight back squat was performed with a 20 kg barbell with weighted plates added to equate 100% of the participant's body weight. The barbell was placed across the shoulders in a high bar position while standing the force plate for data collection. The IMU was placed on the same side of the barbell facing upright. Participants completed 1 set of 3 repetitions at a self-selected foot width and to a depth with which the hip crease obtained a position below the patella in the bottom position. Each participant was instructed to squat while maintaining constant contact between the barbell and their upper back through the duration of the squat and without letting the heels leave the ground. Prior to performing each squat repetition, all participants were instructed to stand perfectly still prior to initiation of the movement to allow for the force plate to determine the mass of the system (barbell + human) which was then used for calculating the variables of interest. Participants were asked to come to a complete stop before being instructed when to perform the next repetition. The variables of interest included mean concentric velocity, mean concentric power, displacement, and duration. Mean concentric velocity and mean concentric power were calculated from averaging the instantaneous velocity and power values collected during the duration of the concentric phase. Displacement was calculated as the depth attained during the eccentric phase of the lift. Duration was collected as the time taken to perform the movement.

3.5 Statistical Analysis

All data of the present study were calculated as mean ± standard deviation (SD). To investigate each of the aforementioned aims of this study, all variables previously mentioned were analyzed by within-subject repeated measures linear regression model. To investigate potential differences in mean concentric velocity (MCV), mean concentric power (MCP), displacement, and duration between the VmaxPro IMU device and the AMTI AccuPower force plate on the back squat at different intensities, a linear regression was be performed with a confidence interval equal to 0.95. A Durbin-Watson test was conducted to test for autoregression as well as a Casewise diagnostic to ensure there were no outliers. Statistical significance (α) was defined as a *p*-value less than 0.05. Further analysis of the data was performed utilizing Bland-Altman plots to show visual representation of the level of relationship agreeance between the paired variables. To investigate potential relationships in mean concentric velocity (MCV), mean concentric power (MCP), countermovement jump depth, countermovement jump height, and duration during the countermovement jump between the VmaxPro IMU device and the

AMTI AccuPower force plate, a linear regression was performed with a confidence interval equal to 0.95. A Durbin-Watson test was conducted to test for autoregression as well as a Casewise diagnostic to ensure there were no outliers. Statistical significance (α) was defined as a *p*-value less than 0.05. Further analysis of the data was performed utilizing Bland-Altman plots to show visual representation of the level of relationship and agreeance between the paired variables. All statistical analyses were conducted using SPSS software (version 27, SPSS, Chicago, IL).

CHAPTER IV – RESULTS

The data revealed a positive correlation between all of the variables of interest, with strong (r= 0.6-0.79) to very strong (r=0.8-1.0) correlation being demonstrated between the two devices in all of the 17 conditional variables measured. All 17 conditional variables demonstrated statistical significance possessing a $p<0.001$. MCV and jump height demonstrated strong correlation in the countermovement jump (0.728 and 0.796, respectively).

MCV demonstrated strong correlations across all three loading conditions: BW back squat (r=0.965), 50% back squat (r=0.907), and 100% back squat (r=0.827). MCP demonstrated very strong correlation for the back squat in BW, 50%, and 100% loading conditions (r= 0.979, 0.960, and 0.887, respectively). Displacement demonstrated strong correlations across the 3 loading conditions of the back squat while total duration demonstrated very strong correlations across all 3 loading conditions (see Table 4.5).

MCV of the BW, 50%, and 100% back squat conditions demonstrated acceptable R^2 values (0.931, 0.823, and 0.684, respectively) demonstrating the percentage of variance that was measured in the AMTI force plate that can be explained by the MCV attained by the VmaxPro IMU unit, pointing to the level of agreeability between devices. MCP mirrored this trend as it demonstrated its highest R^2 value at BW followed by the 50% condition and its lowest value at the 100% condition (0.958, 0.922, and 0.787, respectively). Across the range of the 3 squat loading conditions depth demonstrated the lowest R^2 values.

When considering the correlation values demonstrated across the squat conditions in conjunction with the coefficient of determination values, it is believed that there is a level of agreeance between the two devices in the variables of interest. However, given the significance values, the null hypothesis that there are no significant differences between the measures collected by the two devices is rejected. Upon visual inspection of the means and SD of the variables, discrepancies between devices were observed despite the significant correlations. This leads to the calculation of percent difference of the variable means between the devices (See Tables 4.2 & 4.3). The results of this study show consistent overestimation produced by the VmaxPro when analyzing MCV and MCP in both the squat (32.4% and 32%, respectively) and CMJ (11.93% and 30.96%, respectively) as well as a 29.71% overestimation in jump height. Bland-Altman analysis demonstrated that all variables fell within the 95% confidence interval demonstrating agreeance between devices.

Table 4.1 *Subject Characteristics*

Subjects	Male (n=17)	Female (n=8)	Total (n=25)
		Mean ± SD	
Age (years)	23.9 ± 3.9	23.6 ± 4.3	23.8 ± 2.9
Height (cm)	179.7 ± 5.8	161.5 ± 5.6	173.6 ± 10.2
Body Mass (kg)	88.7 ± 11.1	65.2± 15.3	80.7 ± 16.4
Est. 1RM (kg)	167.9 ± 39	106.8 ± 30.4	148.7 ± 46.5

Table 4.2 *CMJ Descriptive Statistics*

Descriptive Statistics						
Device + Variable	N	Mean		Std. Deviation	Mean	Percent
	Statistic	Statistic	Std. Error	Statistic	Difference	Difference
VmaxPro CMJ MCV (m/s)	24	1.76	0.05	0.28	0.21	11.93%
AMTI CMJ MCV (m/s)	24	1.55	0.03	0.17		
VmaxPro CMJ MCP (W)	24	3318.45	220.10	1078.27	1027.59	30.96%
AMTI CMJ MCP (W)	24	2290.84	146.10	715.76		
VmaxPro CMJ Duration (ms)	24	776.00	28.26	138.43	-42.94	-5.24%
AMTI CMJ Duration (ms)	24	818.94	26.51	129.87		
VmaxPro CMJ Depth (m)	24	0.476	0.025	0.120	0.129	26.26%
AMTI CMJ Depth (m)	24	0.351	0.016	0.076		
VmaxPro CMJ Height (m)	24	0.488	0.017	0.081	0.145	29.71%
AMTI CMJ Height (m)	24	0.343	0.015	0.073		

Table 4.3 *Squat Condition Descriptive Statistics*

Descriptive Statistics						
Device + Condition + Variable	N	Mean		Std. Deviation	Mean	
		Statistic	Std. Error		Difference	
VmaxPro BW MCV (m/s)	24	0.889	0.052	0.253	0.288	32.4%
AMTI BW MCV (m/s)	24	0.601	0.042	0.203		
VmaxPro 50% MCV (m/s)	22	0.816	0.036	0.167	0.204	25%
AMTI 50% MCV (m/s)	22	0.612	0.036	0.170		
VmaxPro 100% MCV (m/s)	25	0.617	0.034	0.172	0.086	14.0%
AMTI 100% MCV (m/s)	25	0.531	0.031	0.157		
VmaxPro BW MCP (W)	24	722.284	63.428	310.731	231.411	32.0%
AMTI BW MCP (W)	24	490.873	46.927	229.892		
VmaxPro 50% MCP (W)	22	969.993	67.457	316.399	234.647	24.2%
AMTI 50% MCP (W)	22	735.346	63.679	298.683		
VmaxPro 100% MCP (W)	25	993.255	73.088	365.441	132.591	13.4%
AMTI 100% MCP (W)	25	860.664	66.288	331.438		
VmaxPro BW Duration (ms)	24	1694.67	75.26	368.72	-89.43	-5.0%
AMTI BW Duration (ms)	24	1784.10	73.16	358.43		
VmaxPro 50% Duration (ms)	22	1862.79	73.67	345.57	-94.41	-4.8%
AMTI 50% Duration (ms)	22	1957.2	81.43	381.94		
VmaxPro 100% Duration (ms)	25	2129.17	82.92	414.58	-142.89	-6.3%
AMTI 100% Duration (ms)	25	2272.1	92.21	461.03		
VmaxPro BW Depth (m)	24	0.553	0.022	0.107	0.118	21.4%
AMTI BW Depth (m)	24	0.435	0.016	0.078		
VmaxPro 50% Depth (m)	22	0.505	0.023	0.108	-0.003	-0.01%
AMTI 50% Depth (m)	22	0.508	0.018	0.084		
VmaxPro 100% Depth (m)	25	0.480	0.021	0.106	-0.043	-8.2%
AMTI 100% Depth (m)	25	0.523	0.018	0.087		

Table 4.4 *CMJ Linear Regression Statistics*

Model Summary					
Model	r	R Square	SEE	Durbin-Watson	Sig.(*p*-value)
CMJ MCV	0.728	0.53	0.121 m/s	1.971	<0.001
CMJ MCP	0.934	0.87	261 W	2.111	<0.001
CMJ Duration	0.839	0.70	72 ms	2.783	<0.001
CMJ Depth	0.908	0.83	0.032 m	2.737	<0.001
CMJ Jump Height	0.796	0.63	0.045 m	1.843	<0.001

Table 4.5 *Squat Condition Linear Regression Statistics*

Model Summary					
Model	r	R Square	SEE	Durbin-Watson	Sig. (*p*-value)
BW MCV	0.965	0.931	0.05 m/s	1.77	<0.001
BW MCP	0.979	0.958	48 W	1.82	<0.001
BW Duration	0.908	0.824	154 ms	2.492	<0.001
BW Depth	0.788	0.621	0.049 m	2.147	<0.001
50% MCV	0.907	0.823	0.07 m/s	1.835	<0.001
50% MCP	0.960	0.922	85 W	2.01	<0.001
50% Duration	0.987	0.974	60 ms	1.351	<0.001
50% Depth	0.755	0.570	0.056 m	1.62	<0.001
100% MCV	0.827	0.684	0.09 m/s	1.991	<0.001
100% MCP	0.887	0.787	156 W	2.106	<0.001
100% Duration	0.950	0.903	146 ms	2.099	<0.001
100% Depth	0.713	0.508	0.063 m	1.347	<0.001

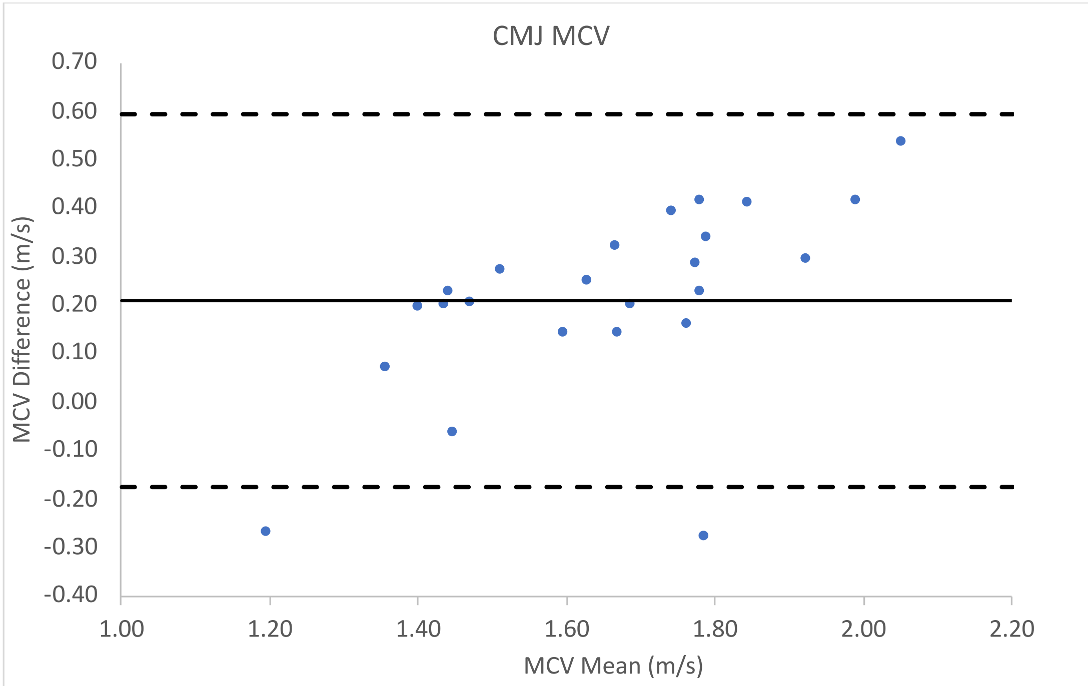

Figure 4.1 *Bland-Altman Scatterplot for CMJ MCV of the VmaxPro versus the Force plate.*

Bland-Altman Scatterplot demonstrating the mean difference between the CMJ MCV values produced by the two devices as depicted by the solid black line. Upper and lower LoA are depicted by the black dashed lines.

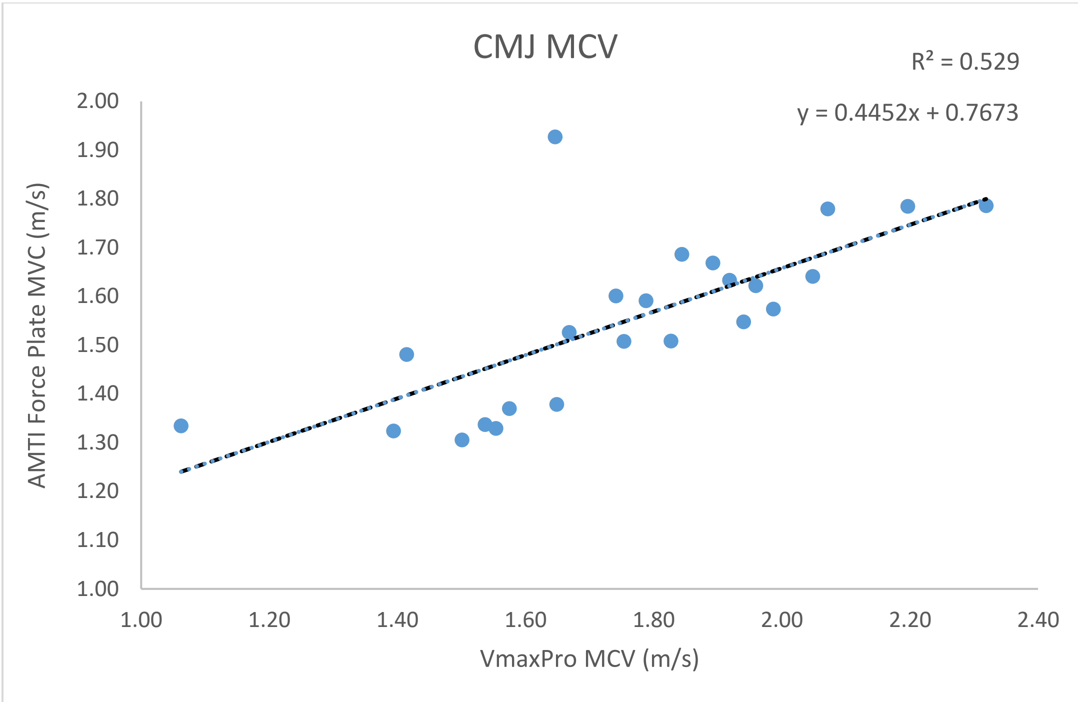

Figure 4.2 *Linear Regression for CMJ MCV.*

Linear regression equation and R^2 values are also pictured.

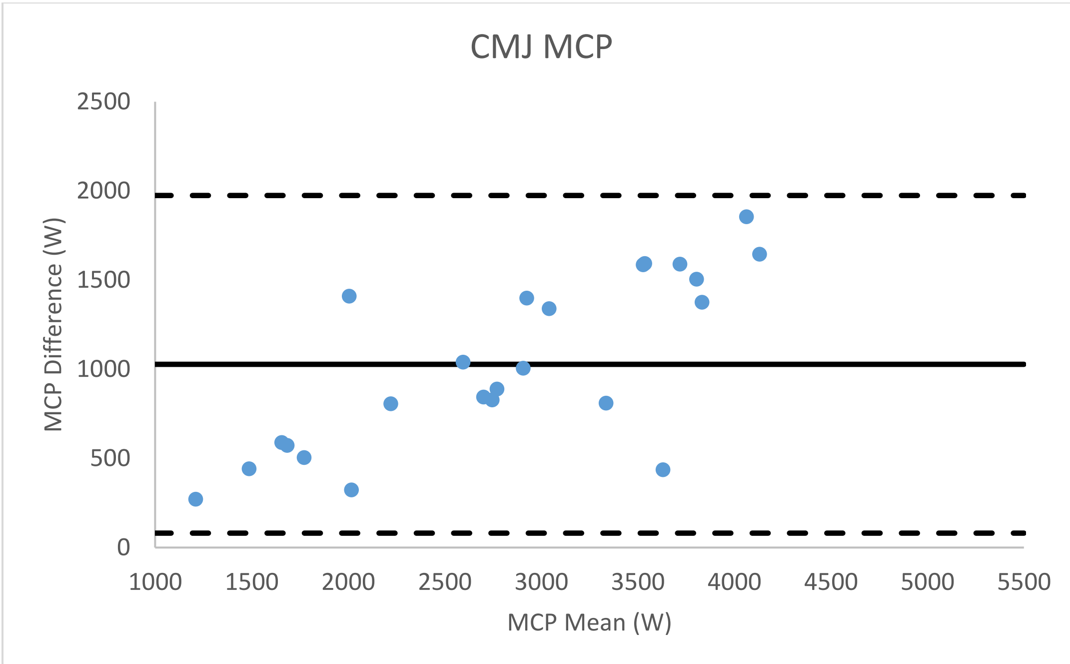

Figure 4.3 *Bland-Altman Scatterplot for CMJ MCP of the VmaxPro versus the Force plate.*

Bland-Altman Scatterplot demonstrating the mean difference between the CMJ MCP values produced by the two devices as depicted by the solid black line. Upper and lower LoA are depicted by the black dashed lines.

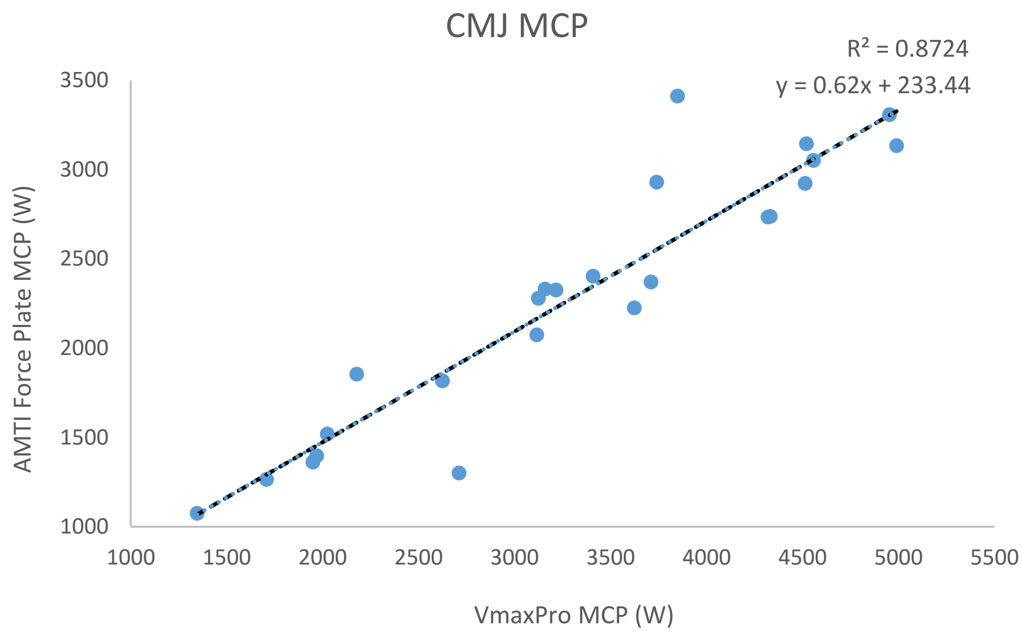

Figure 4.4 *Linear Regression for CJM MCP.*

Linear regression equation and R^2 values are also pictured.

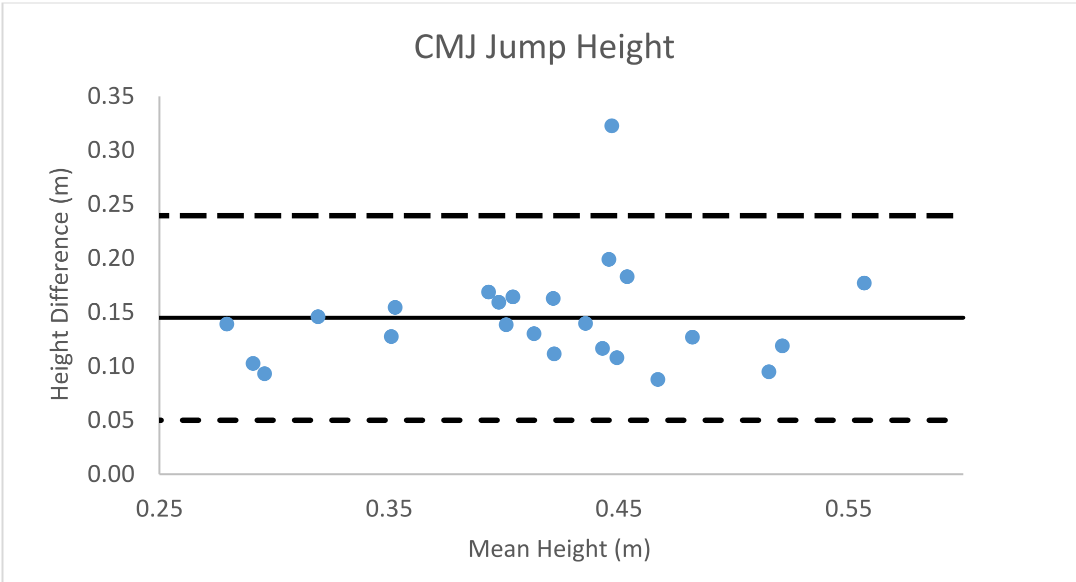

Figure 4.5 *Bland-Altman Scatterplot for CMJ Jump Height of the VmaxPro versus the Force plate.*

Bland-Altman Scatterplot demonstrating the mean difference between the CMJ jump height values produced by the two devices as depicted by the solid black line. Upper and lower LoA are depicted by the black dashed lines.

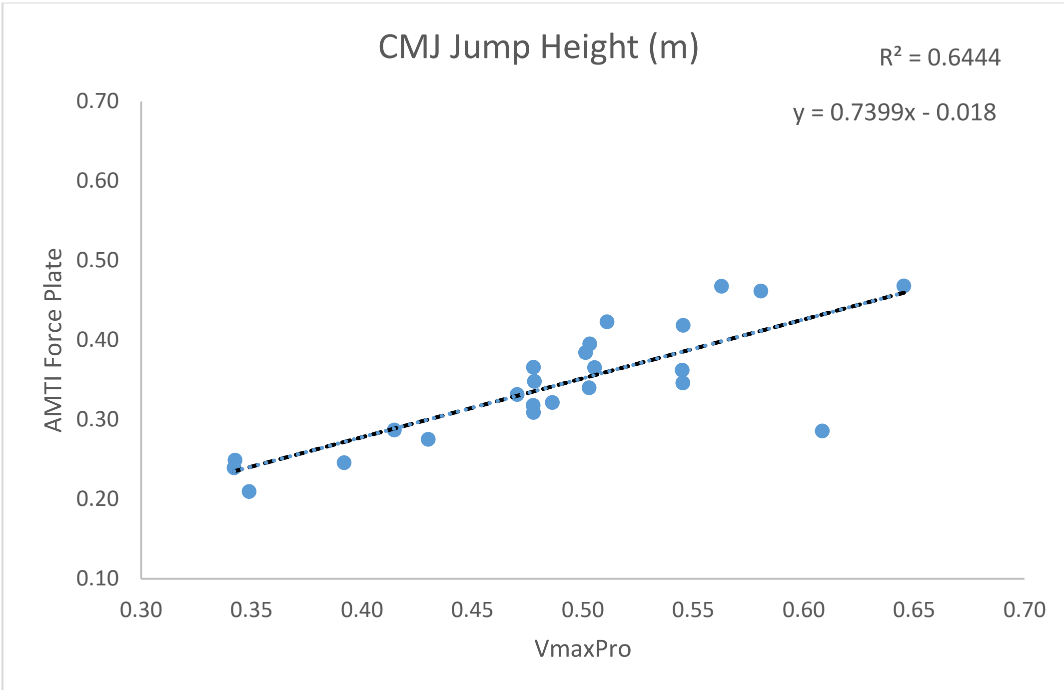

Figure 4.6 *Linear Regression for CMJ Jump Height.*

Linear regression equation and R^2 values are also pictured.

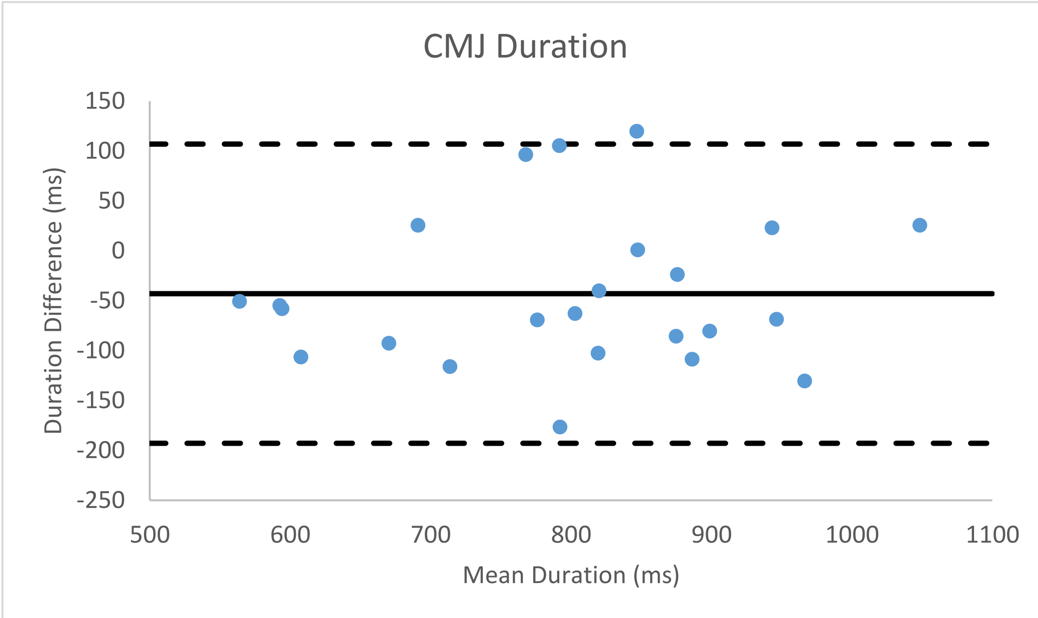

Figure 4.7 *Bland-Altman Scatterplot for CMJ Duration of the VmaxPro versus the Force plate.*

Bland-Altman Scatterplot demonstrating the mean difference between the CMJ duration values produced by the two devices as depicted by the solid black line. Upper and lower LoA are depicted by the black dashed lines.

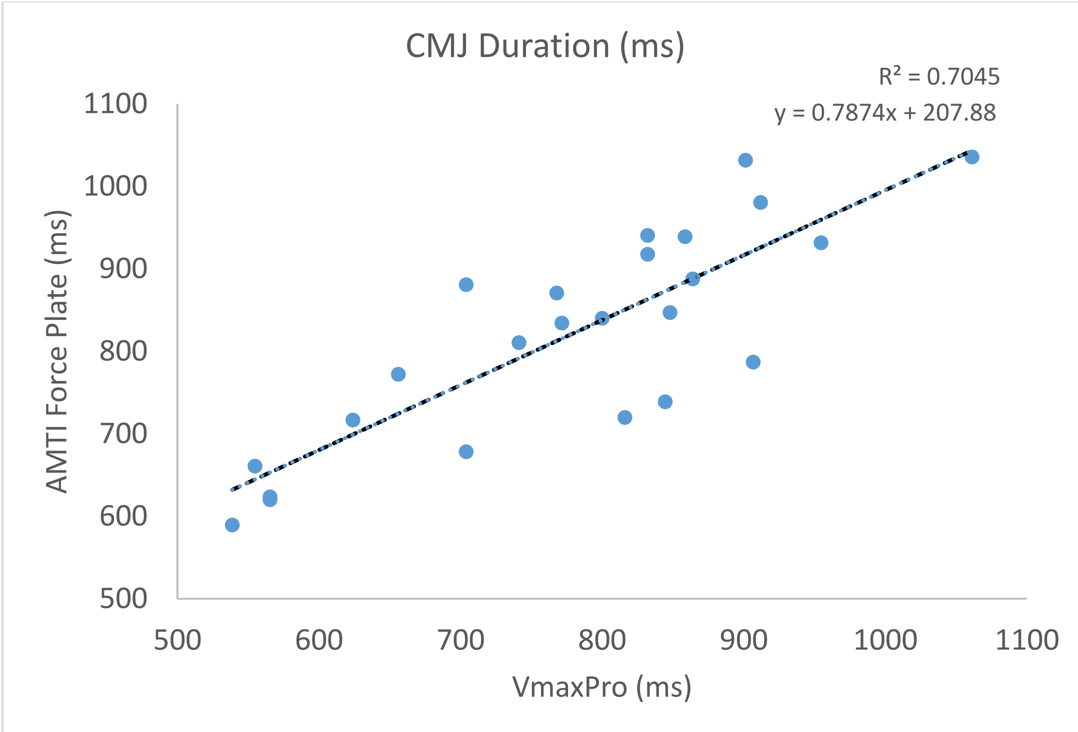

Figure 4.8 *Linear Regression for CMJ Duration.*

Linear regression equation and R^2 values are also pictured.

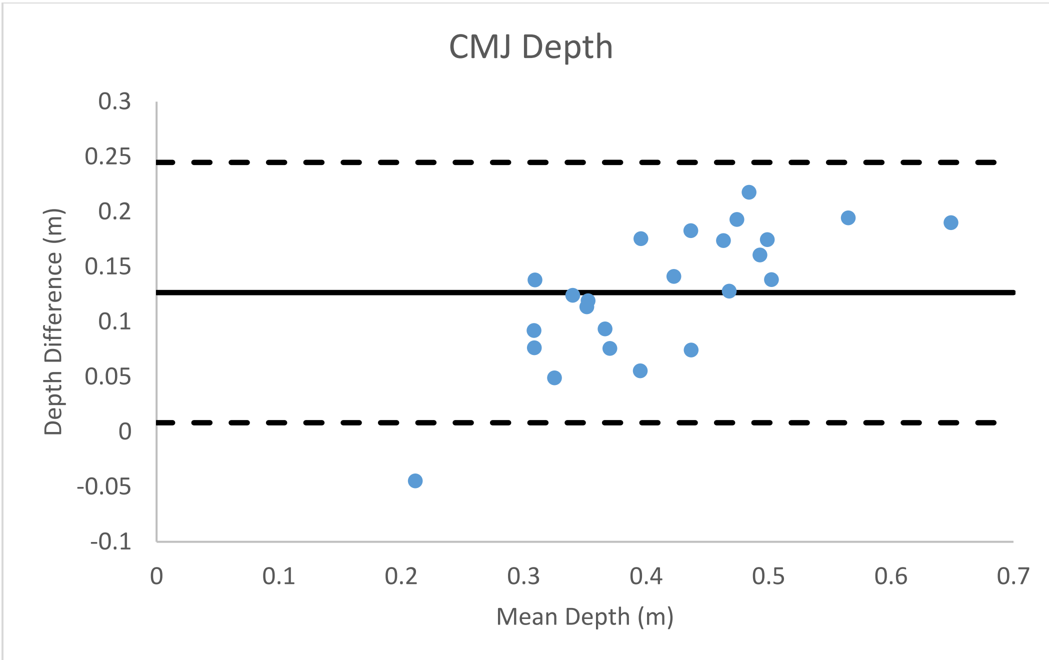

Figure 4.9 *Bland-Altman Scatterplot for CMJ Depth of the VmaxPro versus the Force plate.*

Bland-Altman Scatterplot demonstrating the mean difference between the CMJ depth values produced by the two devices as depicted by the solid black line. Upper and lower LoA are depicted by the black dashed lines.

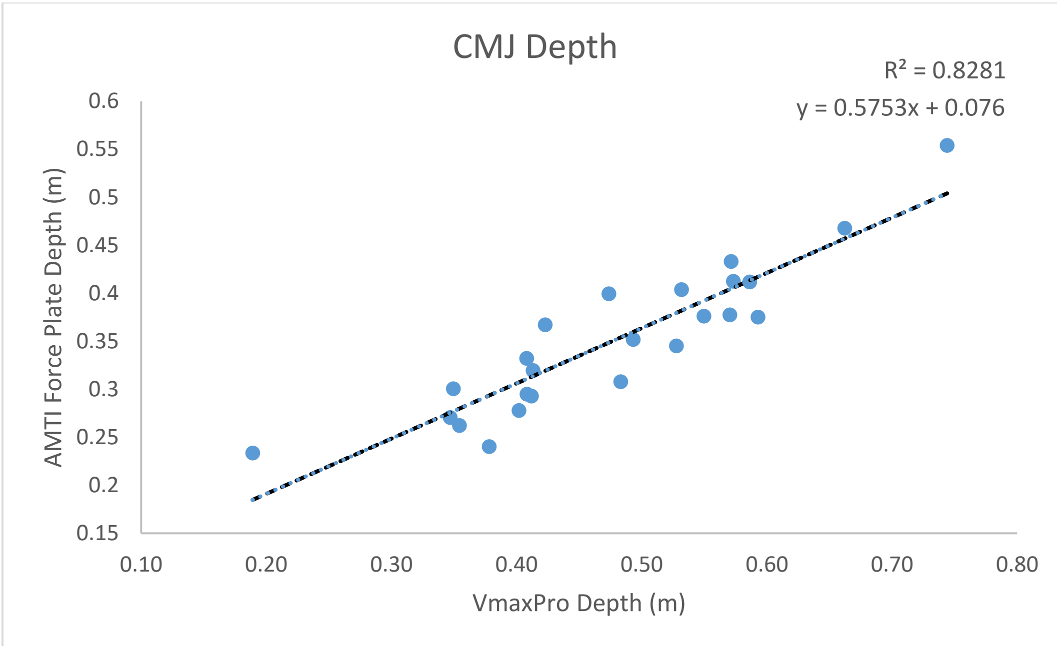

Figure 4.10 *Linear Regression for CMJ Depth.*

Linear regression equation and R^2 values are also pictured.

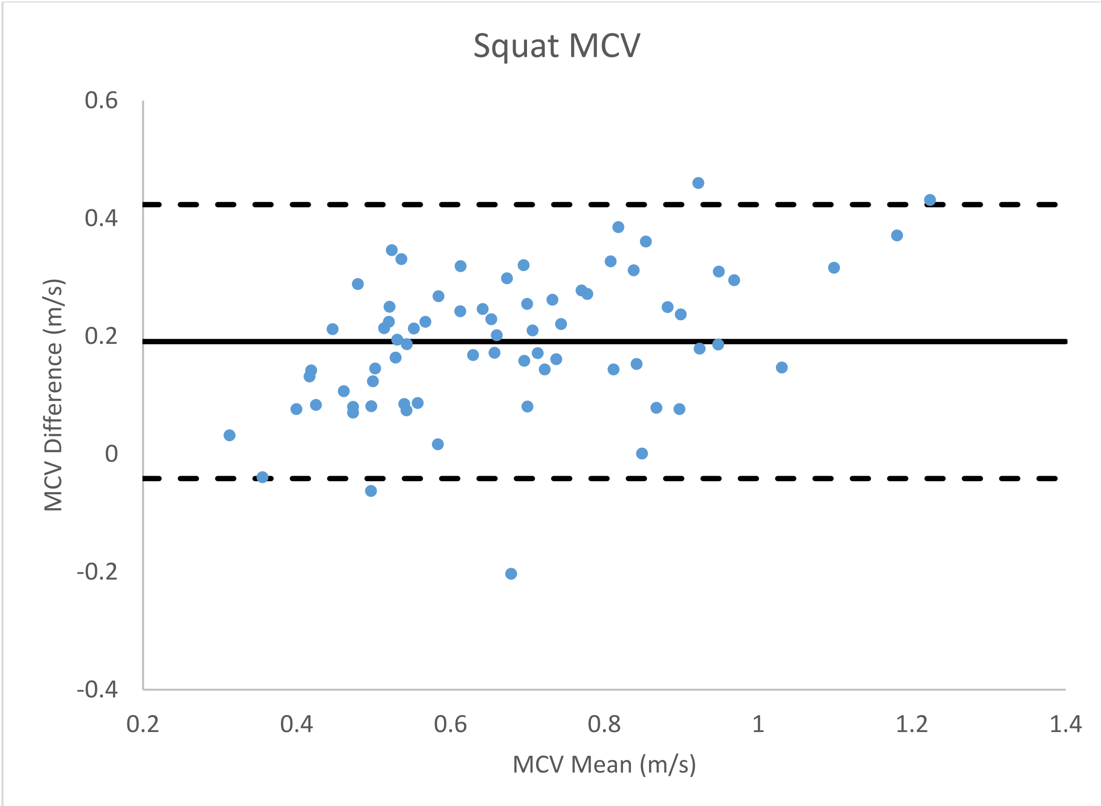

Figure 4.11 *Bland-Altman Scatterplot for MCV of the VmaxPro versus the Force plate for all 3 squat conditions.*

Bland-Altman Scatterplot demonstrating the mean difference between the MCV values produced by the two devices as depicted by the solid black line. Upper and lower LoA are depicted by the black dashed lines.

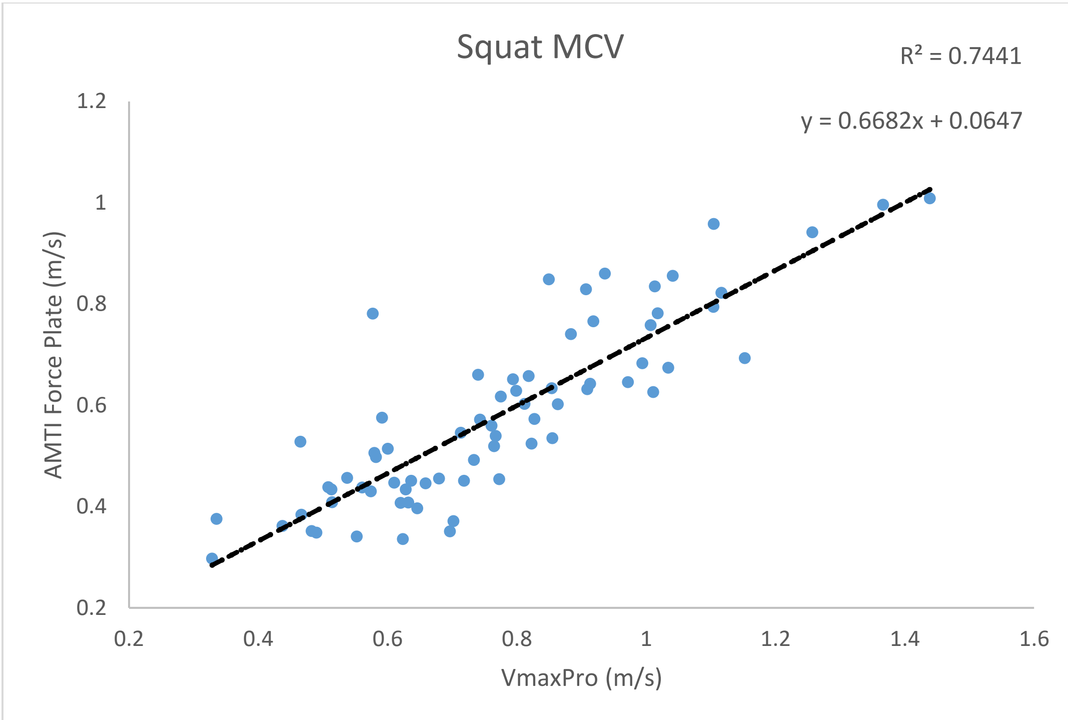

Figure 4.12 *Linear Regression for Squat MCV.*

Linear regression equation and R^2 values are also pictured.

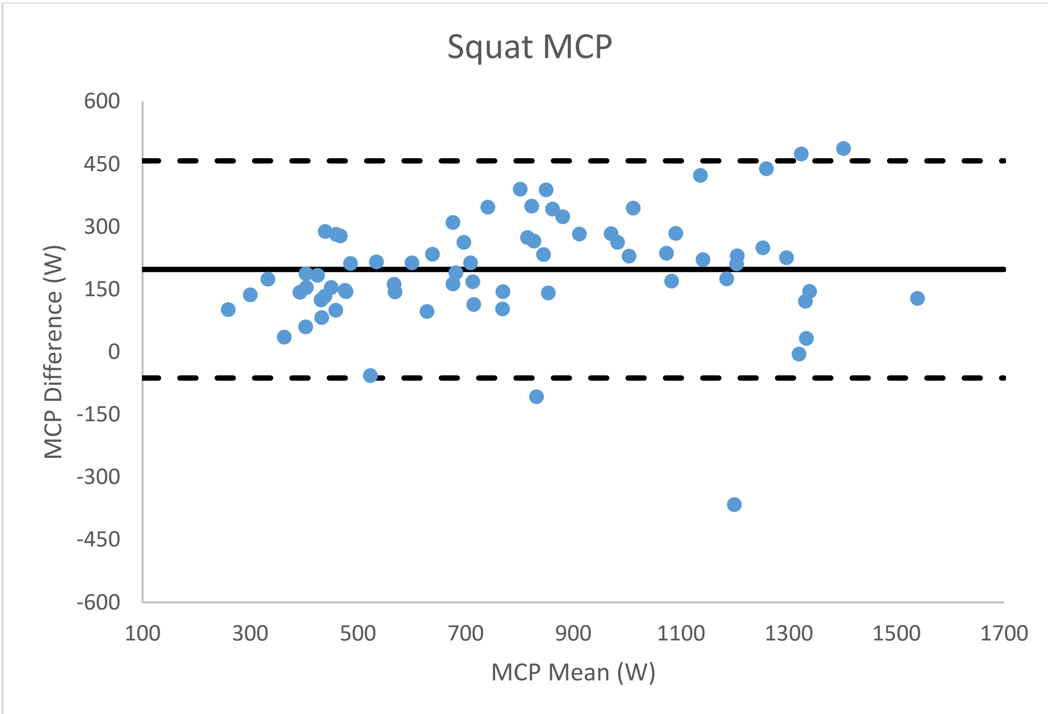

Figure 4.13 *Bland-Altman Scatterplot for MCP of the VmaxPro versus the Force plate for all 3 squat conditions.*

Bland-Altman Scatterplot demonstrating the mean difference between the MCP values produced by the two devices as depicted by the solid black line. Upper and lower LoA are depicted by the black dashed lines.

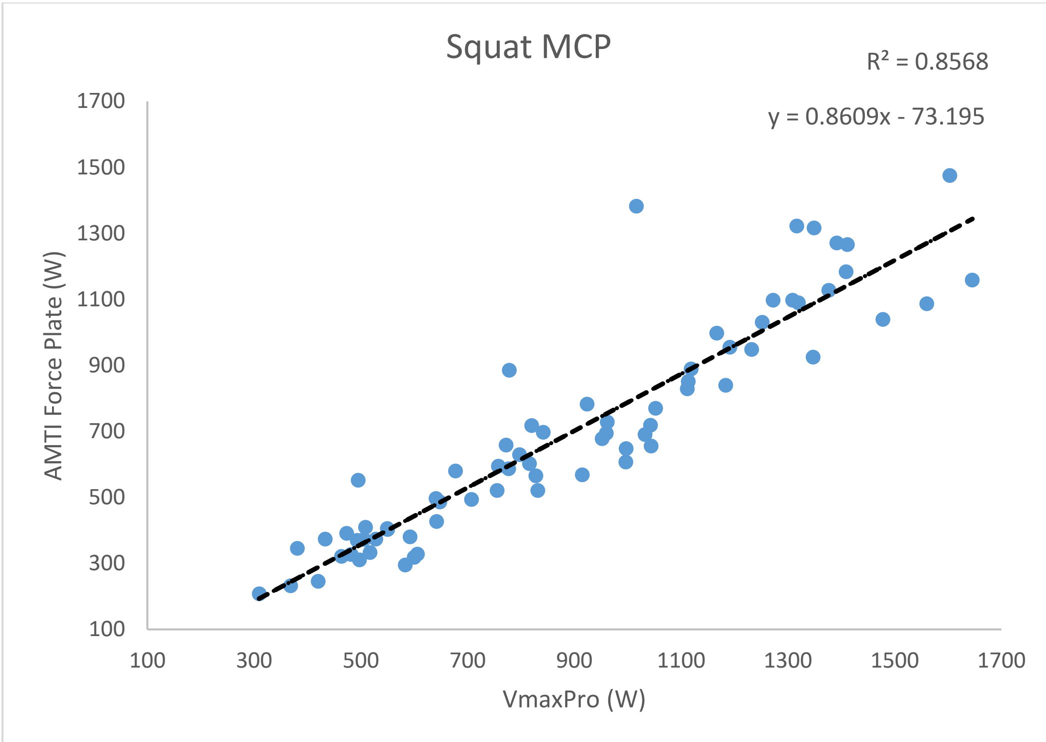

Figure 4.14 *Linear Regression for Squat MCP*.

Linear regression equation and R^2 values are also pictured.

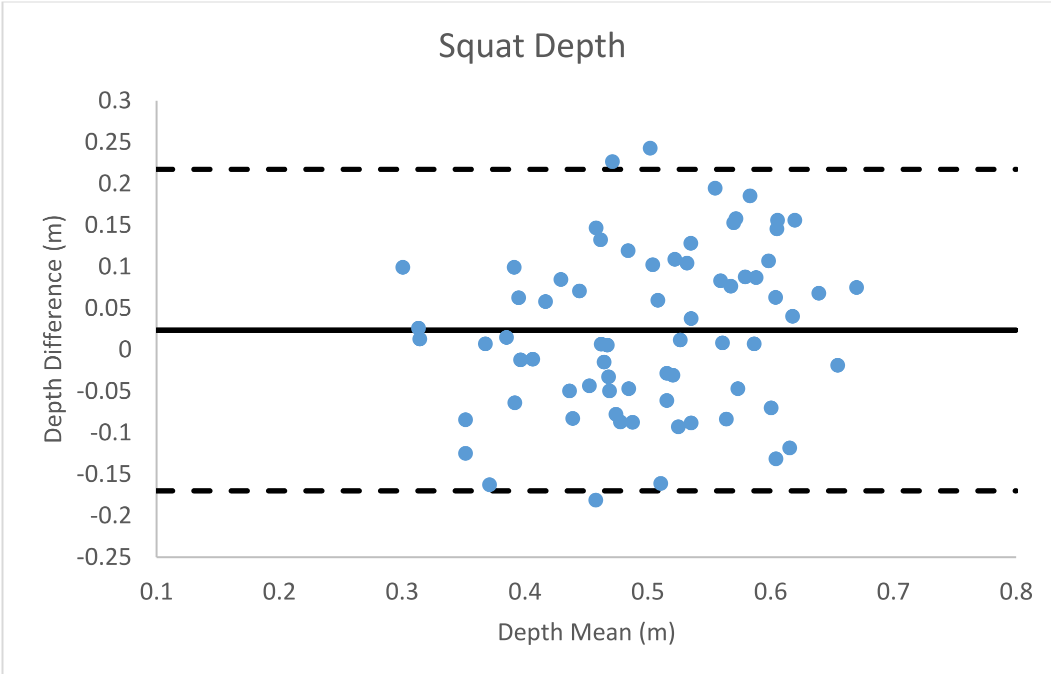

Figure 4.15 *Bland-Altman Scatterplot for Squat Depth values of the VmaxPro versus the Force plate for all 3 squat conditions.*

Bland-Altman Scatterplot demonstrating the mean difference between the squat depth values produced by the two devices as depicted by the solid black line. Upper and lower LoA are depicted by the black dashed lines.

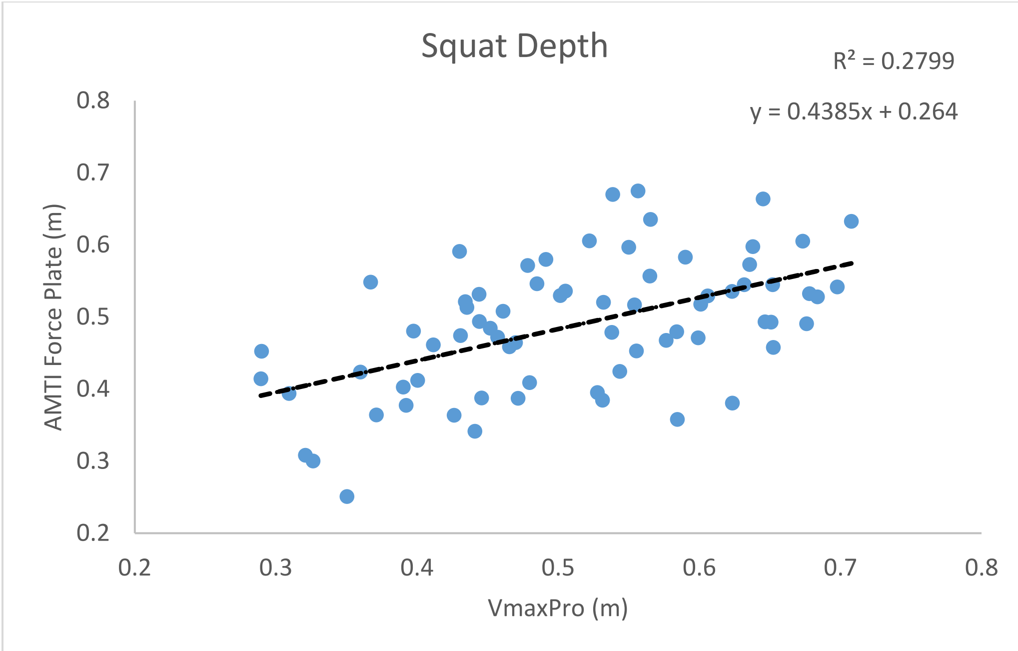

Figure 4.16 *Linear Regression for Squat Depth.*

Linear regression equation and R^2 values are also pictured.

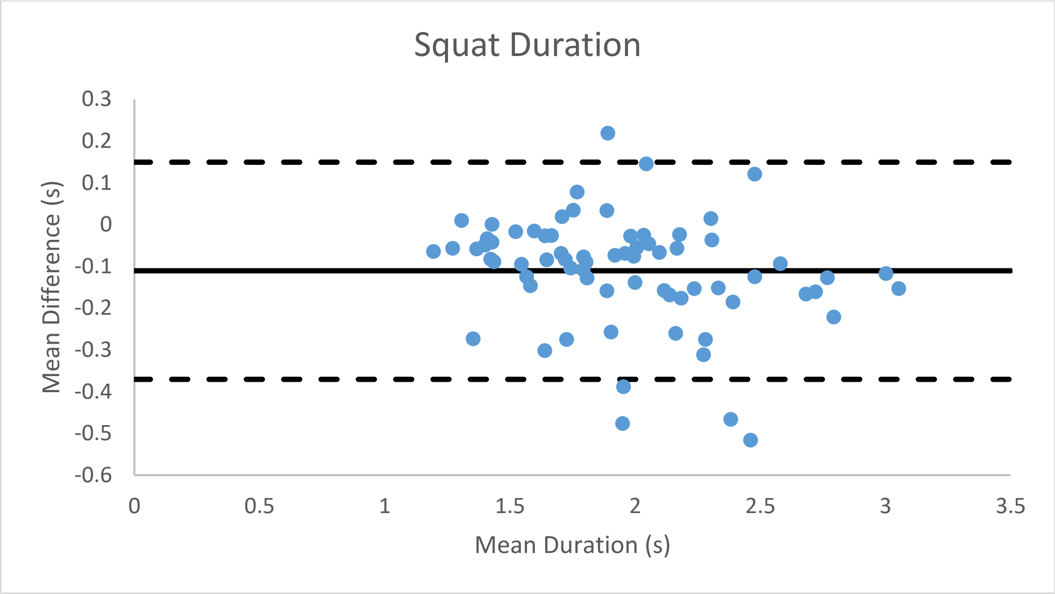

Figure 4.17 *Bland-Altman Scatterplot for Squat Duration values of the VmaxPro versus the Force plate for all 3 squat conditions.*

Bland-Altman Scatterplot demonstrating the mean difference between the squat duration values produced by the two devices as depicted by the solid black line. Upper and lower LoA are depicted by the black dashed lines.

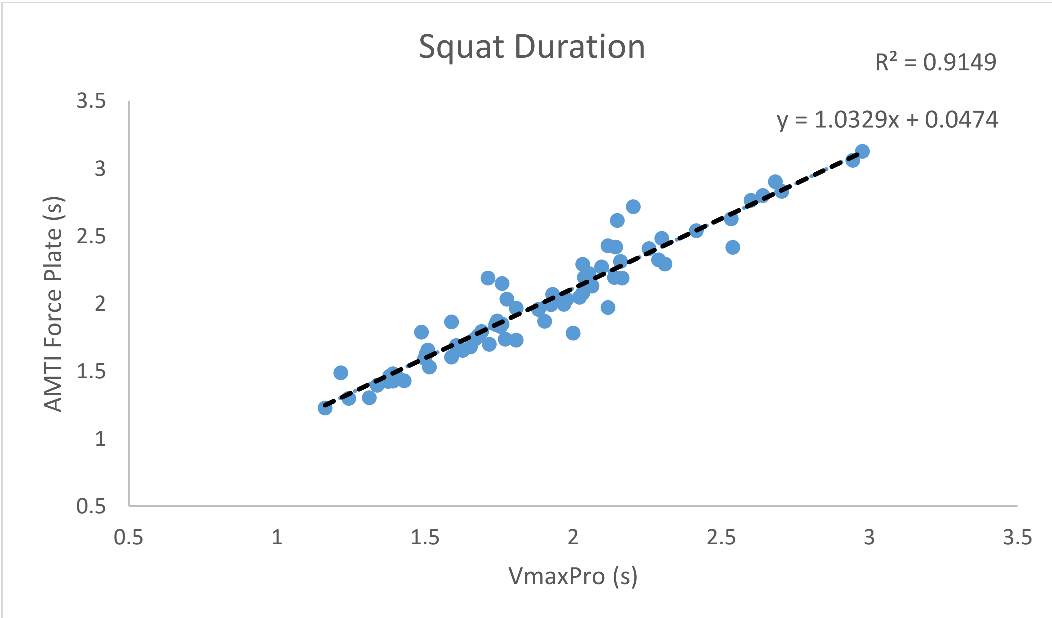

Figure 4.18 *Linear Regression for Squat Duration.*

Linear regression equation and R^2 values are also pictured.

CHAPTER V – DISCUSSION

The purpose of this study was to determine the validity of the kinematic and kinetic variables produced by the VmaxPro as compared to a force plate when performing CMJs and back squats across various loads. The variables of interest consisted of MCV, MCP, duration, displacement (squat depth) in the back squat and MCV, MCP, duration, displacement (counter movement depth), and jump height in the CMJ. This validation study included healthy recreationally trained males and females between the ages of 18-35 with established strength levels and resistance training experience to best assess the validity of the VmaxPro IMU. Before conducting statistical analysis, recognized mistrials were removed from the data set which included one CMJ trial, three 50% BW back squat trials, and one BW back squat trial.

The VmaxPro demonstrated a moderate to strong correlation to the force plate in MCV, MCP, duration, and displacement (depth) across all three loading conditions of the squat. These results share similarities to the results found by Banyard et. al. (2017) when assessing the validity of IMU against a lab-based testing device which consisted of 4 LPTs and a force plate. However, the structure of their study utilized loads based on percentage of 1RM resulting in a wider range in prescribed loads and subsequent velocity ranges being tested. Banyard et. al. (2017) found the Push IMU to only met the criteria set for deeming the device high valid ($r > .70$, $CV \leq 10\%$, and $ES < 0.60$) in MCV at loads below 80% 1RM. The current study utilized loads relative to BW resulting in the use of loads below 70% 1RM for the current study population. Banyard et. al. (2017) reported correlation values >.70 for MCP and MCV for loads ≤ 80% 1RM. The current study reports correlation values >.80 for MCV and MCP across all 3 conditions (BW, 50%, & 100%). Research performed by Held and colleagues (2021) assessed the validity of the VmaxPro against the Speed4Lifts LPT when assessing MCV and barbell displacement in the back squat by having participants work up to a 1RM. The study produced by Held et. al. (2021) deemed the VmaxPro valid when measuring MCV ($r = 0.96$, SE = 0. 01 m/s, LoA = 0.1 m/s, $p = 0.001$) while the current study produced the respective values at BW ($r = 0.97$, SE = 0.05 m/s, $p < 0.001$), 50% ($r = 0.907$, SE = 0.04 m/s, $p < 0.001$), and 100% ($r = 0.827$, SE = 0.03 m/s, $p < 0.001$) for MCV. When comparing the VmaxPro to the Speed4Lifts LPT, a mean difference of 0.001 ± 0.4 m/s was reported, demonstrating a high level of agreeance between the two devices (Held et. al., 2021). The current study demonstrates overestimation of MCV between the devices especially at BW. This finding could be explained by increased noise in the signal as we observed greater horizontal displacement occurring in bar path when participants performed BW squats as compared to 50% and 100% loading conditions. As load on the bar increases, the VmaxPro demonstrates closer agreement in MCV and MCP to the force plate as demonstrated by their mean differences, this points to potentially greater agreeance between the two devices when squatting loads over 70% 1RM, which has yet to be researched. The overestimations in MCV produced near identical levels of percent difference in their corresponding MCP overestimations, which is a direct result of how power is calculated (32.4% vs. 32.0% for BW condition, 25% vs. 24.2% for 50% condition, and 14.0% vs. 13.4% for 100% condition, respectively). Indicating the potential for the VmaxPro to present greater agreeance in power output with loads over 70% 1RM. The current study yields similar results to Held and colleagues (2021), who deemed the barbell displacement produced by the VmaxPro to be invalid due to high LoA (10.69 cm, respectively). The current study found the VmaxPro to be invalid when assessing barbell displacement (depth) as well demonstrating high LoA and low coefficient of determination (see Figure 4.15**,** $R^2 = 0.279$, respectively). The current study demonstrates the VmaxPro to be valid when measuring MCV, MCP, and squat duration with systematic overestimation in MCV and MCP while underestimating squat duration. The findings suggest the VmaxPro should not be utilized to assess squat depth.

When assessing CMJ performance variables the VmaxPro demonstrated strong to very strong correlation to the force plate across all collected variables. Systematic overestimation was present in MCV, MCP, depth, and jump height. The VmaxPro demonstrated a systematic overestimation of jump height with a mean difference of 14.5 cm as compared to the force plate. This overestimation while greater, matches the overestimation in SJ and CMJ height that has been observed in other studies that have compared a LPT to a force plate (O'Donnell et. al., 2017; Wadhi et. al., 2018). The overestimation produced in jump height by the VmaxPro can be explained by the observed overestimation in MCV seen in the current study which demonstrated a mean difference of 0.21 m/s, respectively. Given that jump height is calculated by the estimated take-off velocity ($h= v^2/2g$), an overestimation in velocity would be a direct cause in an overestimation of jump height. Further, the velocity discrepancy could be explained by a large difference in sampling frequency between the two devices. While the force plate sampled at 1000 Hz in the current study, the raw data collected in the VmaxPro Sport Science software collected at a frequency of 62.5 Hz (Blaumann & Meyer-Sports Technology UG, Magdeburg, Germany). With velocity being integrated from acceleration, the discrepancy in time stamps between devices could help explain the overestimation of velocity when compared to the force plate. The overestimation of MCV additionally plays into the role of the overestimation of MCP as the power output at each time stamp is calculated from the matching timestamp's respective velocity and force outputs. Similar reports of overestimation of MCV in the CMJ were reported when researchers looked to validate velocity and power variables of an IMU against a 3D motion capture system and force plate (Lake et. al., 2018). The results from the study by Lake and colleagues (2018) demonstrated an overestimation of 0.340 m/s in MCV and underestimation of 1764 W in MCP, while in the current study the VmaxPro produced an overestimation of 0.21m/s in MCV and an overestimation of 1028 W in MCP.

The linear regression model of the current study demonstrates strong levels of correlation and statistical significance between the force plate and VmaxPro. However, the Bland-Altman analysis demonstrates issues in the utilization of the VmaxPro when assessing MCV, MCP, and depth in the CMJ (see Figures 4.1, 4.3, & 4.9). While the data points fall within the acceptable limits of agreement, a noticeable upward trend is demonstrated for all 3 variables indicating an increase in mean difference as those variables increase. This is problematic for the device's application as the Bland-Altman analysis demonstrates that as MCV and MCP increase, there is a greater gap in agreeance between the two devices. This creates an issue in comparing MCV and MCP outputs between two individuals as the level of overestimation increases as speed of concentric movement increases. Given the variance in overestimation, the VmaxPro doesn't provide a valid measure of CMJ MCV, MCP, or countermovement depth. These issues of increased overestimation in MCV and MCP at greater concentric movement velocities can be explained by the large difference in sampling rate. With the VmaxPro possessing a sampling rate of 62.5 Hz, the device is unable to pick up as many data points to integrate the acceleration data into velocity with as great of accuracy. By speeding up the concentric movement, this further compounds the issue by providing less time to collect data points. While the current study demonstrates issues in the utilization for the VmaxPro in assessing CMJ MCV and MCP, the device does show potential use for assessing CMJ jump height and duration. Although, the VmaxPro overestimates jump height with a mean difference of 14.5 cm, the Bland-Altman analysis demonstrated a consistent level of agreeance between the force plate and VmaxPro. Which is demonstrated across a wide range of jump heights (see Figure 4.5). Despite the overestimation, the consistent level of agreeance across the range of jump heights proves the VmaxPro to be a reasonably valid device for assessing CMJ jump height with an overestimation bias.

In conclusion, the VmaxPro provides a reasonably valid device for assessing duration and jump height when assessing CMJ performance as compared to the force plate while demonstrating overestimation bias. Given the current results, strength and conditioning practitioners could potentially utilize the VmaxPro for assessing CMJ performance. With the current study demonstrating strong correlation to the force plate for measuring CMJ variables such as jump height and duration, the VmaxPro could potentially track popular CMJ derived variables such as RSImod. The VmaxPro potentially provides a cost-efficient solution for assessing certain CMJ variables, however strength and conditioning practitioners should be aware of the overestimation of values. Future studies should assess the inter-device and between day reliability of these measures to ensure the usage of the device to track trends over the course of time. Additionally, further research is need when utilizing the VmaxPro to assess CMJ performance in elite and collegiate athletes. Given that the current study demonstrated an increased overestimation in MCV as the velocity of the CMJ increased, the transfer of CMJ testing in collegiate athletics needs further research as Sauls & Dabbs (2017) demonstrated significantly greater CMJ peak velocity values produced by collegiate athletes as compared to recreational athletes. Future studies should also assess the effects of VmaxPro positioning in an attempt to optimize the accuracy of results. When assessing back squat performance variables, the VmaxPro proves as a reasonably valid device for assessing MCV, MCP, depth, and duration. However, strength and conditioning practitioners and customers alike should be aware of overestimation bias. Future studies should assess the validity of the VmaxPro in comparison to the force plate with loads greater than 70% 1RM to gain better understanding of the device's performance at practical training loads. With further research, limitations of the current VmaxPro device can be properly identified as well as finding potential ways to optimize the device's ability to assess CMJ performance.

APPENDIX A – Device and Lab Setup

Figure A.1 *Lab Setup*

Setup of Barbell with simultaneous data collection produced by the VmaxPro IMU (placed on barbell) and AMTI Force plate (gray platform).

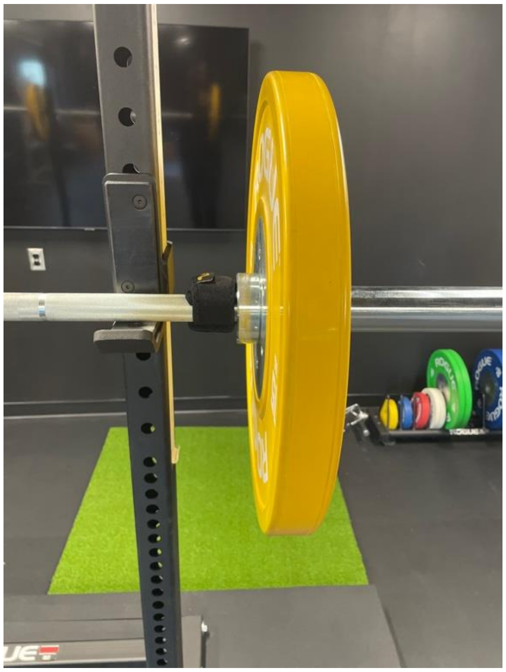

Figure A.2 *VmaxPro Placement*

Setup of VmaxPro on the right side of the barbell next to the collar as recommended by the manufacturer.

APPENDIX B – IRB Approval Letter

Office *of*
Research Integrity

THE UNIVERSITY OF SOUTHERN MISSISSIPPI.

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NOTICE OF INSTITUTIONAL REVIEW BOARD ACTION

The project below has been reviewed by The University of Southern Mississippi Institutional Review Board in accordance with Federal Drug Administration regulations (21 CFR 26, 111), Department of Health and Human Services regulations (45 CFR Part 46), and University Policy to ensure:

- The risks to subjects are minimized and reasonable in relation to the anticipated benefits.
- The selection of subjects is equitable.
- Informed consent is adequate and appropriately documented.
- Where appropriate, the research plan makes adequate provisions for monitoring the data collected to ensure the safety of the subjects.
- Where appropriate, there are adequate provisions to protect the privacy of subjects and to maintain the confidentiality of all data.
- Appropriate additional safeguards have been included to protect vulnerable subjects.
- Any unanticipated, serious, or continuing problems encountered involving risks to subjects must be reported immediately. Problems should be reported to ORI via the Incident submission on InfoEd IRB.
- The period of approval is twelve months. An application for renewal must be submitted for projects exceeding twelve months.

PROTOCOL NUMBER:	21-176
PROJECT TITLE:	The Validity of the VmaxPro during Countermovement Jump and Back Squat Performance
SCHOOL/PROGRAM	Kinesiology
RESEARCHERS:	PI: Hunter Haynes Investigators: Haynes, Hunter~Galloway, Riley~
IRB COMMITTEE ACTION:	Approved
CATEGORY:	Expedited Category
PERIOD OF APPROVAL:	02-Dec-2021 to 01-Dec-2022

Donald Sacco, Jr.

Donald Sacco, Ph.D.
Institutional Review Board Chairperson")

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